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DEVELOPMENT OF A POWER SYSTEM STABILIZER TOOLBOX FOR UTILITY APPLICATIONS

By

Lili Bu

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Abstract

This thesis pursues an extensive study on the implementation of Power System Stabilizer (PSS) design/tuning to enhance the damping of power system oscillation. The objective of this project is to develop a toolbox that automates the PSS design/tuning process.

A PSS design/tuning program package was developed in this thesis as one of the basic analytical tools for investigating power system oscillations. The characteristics and mathematical model of oscillatory stability problems were described, and the basic concepts and design/tuning method of PSS were discussed to mitigate the power system oscillation. The proposed parameter setting method underlie this program was analyzed, along with illustration of performance evaluation of the designed/tuned PSS. Advantages of the developed toolbox was demonstrated by case study results, it was shown that the PSS design/tuning approach used in this project is straightforward and simple for industry applications, especially for large-scale power systems, and it is further proved that the design/tuning of PSS is a very attractive and effective solution to electromechanical oscillation-damping problems.

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To My Parents

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List of Symbols

PSS	Abbreviation of power system stabilizer
AVR	Abbreviation of automatic voltage regulator
SVC	Abbreviation of static var compensators
$FACTS$	Abbreviation of flexible AC transmission system
$TCSC$	Abbreviation of thyristor controlled series capacitor
$SSAT$	Small Signal Analysis Tool
$TSAT$	Transient Security Assessment Tool
T_e	Electrical torque
T_s	Synchronizing torque coefficient
T_D	Damping torque coefficient
P_e	Electric power at generator terminals
P_m	Generator mechanical power
ΔP_a	Generator accelerating power
V_{ref}	Voltage reference of voltage regulator
H	Rotor mechanical inertia constant
$\Delta\omega$	Rotor angular speed deviation
δ	Rotor angular
T_l	Lead/lag time constant of power system stabilizer
T_w	Washout time constant of power system stabilizer
K	Gain of power system stabilizer
K_{max}	Maximum gain of power system stabilizer
K_{min}	Minimum gain of power system stabilizer
ζ	Damping ratio of power system oscillation mode
λ	Eigenvalue of power system oscillation mode
t	Time in second

f	Frequency in Hz
ω	Frequency in rad/sec
pu	Per unit
s	Laplace operator
Δ	Small change
$\sum$	Summation

Chapter 1

Introduction

The purpose of this introduction chapter is to provide a general description of the power system stability. The basic characteristics of power system oscillation are briefly described. Control and mitigation of power system oscillation are also introduced. This chapter ends with a statement of the thesis objective and outline of how to achieve the objective.

1.1 An Introduction of Power System Stability

Power system stability was first recognized as an important problem in the 1920s. Since then, power system stability has obtained a much broader perspective and has become an independent discipline. Power system stability may be broadly defined as the property of a power system that enables it to retain a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [35].

It has been a common practice to classify power system stability into two forms: rotor angle stability and voltage stability. A detailed classification of power system stability is discussed in Reference 35.

Rotor angle stability is the ability of the interconnected synchronous machines of a power system to remain in synchronism. This stability problem involves the study of the electromechanical oscillations inherent in power systems. Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions after being subjected to a disturbance [35].

From the beginning, for convenience of analysis, to gain a better understanding of the nature of stability problems and to develop solutions to the problems, it has been the usual practice to classify rotor angle stability into two broad categories: small-signal stability and transient stability.

Small-signal stability is the ability of a power system to maintain synchronism under small disturbances. Such disturbances occur continually in the system because of small variations in loads and generation. These disturbances are considered sufficiently small for linearization of system equations to be permissible for purposes of analysis. Transient stability is the ability of a power system to maintain synchronism when subject to a severe transient disturbance and is related to the transient period. Stability is determined by both the initial operating state of the system and the severity of the disturbance [35].

Until now, much of the effort and interest related to rotor angle stability has been focused on transient stability, and the power system is designed and operated so as to meet a set of reliability criteria concerning transient stability. However, in recent years, the small-signal stability has caused increasing concern for many power pools in North America, and the analysis of small-signal stability is becoming more and more widespread.

Small-signal instability can be of two forms:

- Steady increase in rotor angle due to lack of sufficient synchronizing torque, or
- Rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

Figure 1.1 shows a spontaneous oscillation that occurred in Western System Coordinating Council (WSCC) on August 10, 1996.

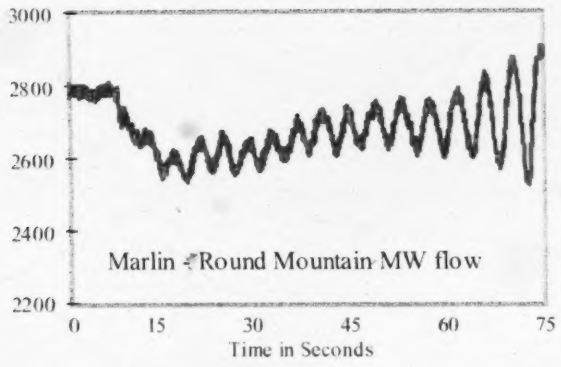


Figure 1.1 Spontaneous oscillations in WSCC, August 10, 1996.

This oscillation emerged from the conditions of high power transfer on long paths that had been progressively weakened through a series of fairly routine resources losses [9].

The nature of small-signal stability problem depends on a number of factors including the initial operating condition, the transmission system strength, and the type of generator excitation controls used.

1:2 Brief Overview of Power System Oscillations

As power systems evolve, they are operated ever closer to transient and steady state stability limits. System stability characteristics are largely influenced by the strength of the transmission network, and the lack of sufficient synchronizing torque is the principal cause of system instability. The use of continuously acting voltage regulators contributed to the improvement of the small-signal stability. In the 1950s and 1960s, utilities were primarily concerned with the transient stability, but less attention was paid to the damping of system oscillations. This situation has been gradually changing, however, since the late 1960s. Significant improvements in transient stability performance have been achieved through the use of high-speed fault clearing, high

response exciters, and special stability aids. This trend has been accompanied by an increased tendency of the power system to exhibit oscillatory instability. The poorly damped oscillations have become a source of concern in many systems, and they are now becoming more commonplace and are increasingly being identified in the planning and operating studies.

In today's practical power systems, insufficient damping of oscillation is the main problem of small-signal stability. Power system oscillation problems may be either local or global in nature [35].

Local problems involve a small part of the system. They may be associated with rotor angle oscillations of a single generator or a single plant against the rest of the power system. Such oscillations are called local plant mode oscillations. The stability problems related to such oscillations are similar to those of a single-machine infinite bus system. Most commonly encountered small-signal stability problems belong to this category. Local problems may also be associated with oscillations between the rotors of a few generators close to each other. Such oscillations are called inter-machine or interplant mode oscillations. Usually, the local plant mode and interplant mode oscillations have frequencies in the range of 0.7 to 3.0 Hz. Other possible local problems include instability of the modes associated with the controls of equipment such as generator excitation systems, HVDC converters, and static var compensators (SVC). The problems associated with control modes are due to inadequate tuning of the control system. In addition, these controls may interact with the dynamics of the turbine-generator shaft system, causing instability of the torsional mode oscillations.

Global small-signal stability problems are caused by interactions among large groups of generators and have widespread effects. They involve oscillations of a group of generators in one area swinging against a group of generators in another area. Such oscillations are called inter-area mode oscillations. Large interconnected systems usually have two distinct forms of inter-area oscillations:

a) A very low frequency mode involving all the generators in the system. The system is essentially split into two parts, with generators in one part swinging against machines in the other part. The frequency of this mode of oscillation is on the order of 0.1 Hz to 0.3 Hz.

b) Higher frequency modes involving subgroups of generators swinging against each other. The frequency of these oscillations is typically in the range of 0.4 to 0.7 Hz.

1.3 Control of Power System Oscillation

As illustrated above, power system oscillations contain many modes of oscillation due to the generator rotor masses swing relative to one another. Under disturbed conditions, the change in the electrical torque of a synchronous machine, ΔT_e, which influences the machine oscillations, can be conceptually split into two components [35]:

$$\Delta T_e = T_s \Delta\delta + T_D \Delta\omega \qquad (1\text{-}1)$$

where

$T_s \Delta\delta$ is the synchronizing torque component, and

$T_D \Delta\omega$ is the damping torque component.

The synchronizing component "holds" the machines together and is important for the transient stability of the system following large disturbances. For small disturbances, the synchronizing component of torque determines the frequency of an oscillation. The damping component determines the decay of oscillations and is important for the system stability following the recovery from the initial swing [9].

Damping is influenced by many system parameters, and can sometimes become negative in the presence of controls. Negative damping can lead to spontaneous growth of oscillations until relays begin to trip system elements or a limit cycle is reached.

There are a number of common solutions that can be evaluated as mitigation measures for oscillation [6]:

- Modify existing controls
- Add new controls
- Add new transmission and/or generation facilities
- Impose operating restrictions
- Some combination of the above

The power system devices, which have the potential for contributing to the damping of the oscillations, include Power System Stabilizer (PSS), HVDC link modulation, SVC modulation, Thyristor Controlled Series Capacitor (TCSC), Flexible AC Transmission System (FACTS) modulation etc. [9]. In selecting devices and controls to be applied for mitigating power system oscillations, one should at first consider using carefully tuned PSS on the major generating units affected by the oscillations. This is because of the effectiveness and relatively low cost of PSS. Other devices such as HVDC, SVC and FACTS are also capable of controlling damping oscillations, however, they are installed primarily on the basis of other system considerations, and their capital cost is prohibitive for using solely for damping system oscillations. Addition of a new device into the power system for the primary purpose of damping is the least preferable action [9].

1.4 Thesis Objective

The design and tuning of PSS have significant influence on their effectiveness in mitigating power system oscillations. The theoretical foundation and design methodology

of PSS, and field-testing procedure have been developed by many applications. Industry-accepted procedures for PSS design and tuning have been established. However, application of these procedures requires working with utilities' production system models and using specialized analysis software tools. This process is not intuitive and it often makes a design/tuning task lengthy, confusing or sometimes erroneous.

In this project, the major concern is to develop a tool that automates the PSS design/tuning process. The basic approach is to utilize the proven design/tuning methods and specialized analysis tools, to integrate these into a single PSS design/tuning toolbox. The emphasis is that, with a production power system model and a straightforward design/tuning objective, this toolbox goes through all necessary computation steps in a PSS design/tuning cycle to give optimally designed or tuned PSS parameters and the corresponding performance indices.

The scope of this thesis consists of the following:

1) Literature review for PSS design/tuning methods.

2) Determination of effective locations for PSS installation/tuning in order to provide the best damping to inter-area modes.

3) Tuning of the PSS parameters for either local or inter-area modes.

4) Design of new PSS according to performance requirements.

5) Performance evaluation of designed/tuned PSS in both frequency and time domains.

The PSS design/tuning toolbox developed for this project works in MATLAB, with connection to a commercial modal analysis tool (Small Signal Analysis Tool-SSAT)

and time-domain simulation tool (Transient Security Assessment Tool-TSAT), developed by Powertech Labs Inc..

1.5 Outline of Thesis

The rest of this thesis is organized as follows:

Chapter 2 presents the fundamental theory for power system oscillation analysis and PSS control. Characteristics and analysis method of power system oscillation are introduced. Basic idea of PSS and various methods for PSS design/tuning are discussed. This chapter provides the basic analytic tools for small-signal stability analysis and PSS design/tuning methods.

The details on the proposed PSS design/tuning toolbox are given in Chapter 3. The basic approach and general design procedure that underlie this program, such as considerations of different PSS types, determination of PSS location, PSS parameters setting, PSS design/tuning logic, and PSS design/tuning tools etc., are described. Some factors affecting PSS design/tuning are also analyzed.

For the purpose of verifying the toolbox developed for this project, Chapter 4 presents the case studies. Two cases based on practical power systems are studied with different study objectives. The results of case studies are analyzed and compared to get a full understanding of the proposed PSS design/tuning approach. The effectiveness and advantages of this PSS design/tuning toolbox is demonstrated by the analysis of these large and complex cases.

Finally, Chapter 5 gives some conclusions of this project and some ideas for future investigation.

Chapter 2

Power System Oscillation Analysis and PSS Control

2.1 Power System Oscillation and Analysis

In Chapter 1, the problem of power system oscillations has been briefly described. In this section, characteristics and analysis methods for power system oscillation are explained.

2.1.1 Characteristics of Power System Oscillation

The following types of power system oscillations have been observed in today's power systems [9]:

1) Local modes or machine-system modes

These modes are associated with the swing of units at a generating station with respect to the rest of the power system. The term local is used because the oscillations are localized at one station or a small part of the power system. Local mode oscillation problems are the most commonly encountered among the oscillation modes. Some of these problems are caused by the action of the automatic voltage regulator (AVR) of generating units operating at a high output and feeding into the weak transmission networks; the problem is more pronounced with a high response excitation system. And some others can be caused by bad tuning of controllers, such as PSS. The local oscillations typically have natural frequencies in the range of 0.7 to 3.0 Hz. Their characteristics are well understood and adequate damping can be readily achieved by using supplementary control of excitation systems [9].

2) Inter-area modes

These modes are associated with the swing of many machines in one part of the system against machines in other parts. They are caused by two or more groups of closely coupled machines being interconnected by weak ties [35]. The natural frequency of these oscillations is typically in the range of 0.1 to 1.0 Hz. The characteristics of inter-area modes of oscillations are complex and in some respects significantly differ from the characteristics of local modes [9].

3) Control modes

These modes are associated with generating units and other controls. Poorly tuned exciters, speed governors, HVDC converters and SVC are the usual causes of instability of these modes [35].

4) Torsional modes

These modes are associated with the turbine-generator shaft system rotational components. Instability of torsional modes may be caused by interaction with excitation controls, speed governors, HVDC controls, and series-capacitor-compensated lines [35].

Among the various types of power system oscillations, normally the inter-area type presents the greatest challenge. The controllability of inter-area modes is a complex function of many factors. Not only the location of unit, but also load characteristics, in particular, have a major influence on the stability of inter-area modes. Excitation system and speed-governing systems also have effects on inter-area modes [9].

2.1.2 Modal Analysis of Linearized Power System

Modal analysis is the fundamental theory for small-signal stability analysis. It involves the determination of the characteristic modes of a system model linearized around a specific operating point [35]. The existing analytical tools of modal analysis can provide users with the ability to assess system oscillatory stability, locate the sources of

any oscillatory mode, and either retune existing controllers or design supplementary controls to stabilize power system oscillations [9].

2.1.2.1 Basic Concepts of Modal Analysis and Formulation

1. Linear Representation of Power System Model

The simulation of power system dynamics is now a routine procedure for system planning and operation. These simulations are based on the solution of the nonlinear algebraic-differential equations of a power system, which are in the general form [9]:

$$\begin{aligned} \frac{\mathbf{dx}}{\mathbf{dt}} &= \mathbf{f(x,v,q)} \\ \mathbf{0} &= \mathbf{g(x,v,q)} \\ \mathbf{y} &= \mathbf{h(x,v)} \end{aligned} \tag{2-1}$$

where

$\mathbf{x}$ is a vector of dynamic variables referred to as "states",

$\mathbf{v}$ is a vector of network voltages,

$\mathbf{q}$ is a vector of disturbances or control inputs,

$\mathbf{y}$ is a vector of monitored outputs for control or information,

$\mathbf{f}$ represents the nonlinear dynamic characteristics of the system's dynamic components,

$\mathbf{g}$ represents the nonlinear network equations,

$\mathbf{h}$ represents the nonlinear output equation.

In modal analysis, these nonlinear equations are linearized around an operating point by truncating a Taylor series expansion of $\mathbf{f}$ and $\mathbf{g}$ to the first order term. Since it is assumed that the system is in steady-state at the operating point defined by $\mathbf{x}_0$ and $\mathbf{v}_0$, then $\mathbf{f}(\mathbf{x}_0,\mathbf{v}_0)$ and $\mathbf{g}(\mathbf{x}_0,\mathbf{v}_0)$ are both zero. The linearized equations are:

$$\begin{aligned}
\frac{\mathbf{d}(\Delta\mathbf{x})}{\mathbf{dt}} &= \frac{\partial \mathbf{f}}{\partial \mathbf{x}}\Delta\mathbf{x} + \frac{\partial \mathbf{f}}{\partial \mathbf{v}}\Delta\mathbf{v} + \frac{\partial \mathbf{f}}{\partial \mathbf{q}}\Delta\mathbf{q} \\
\mathbf{0} &= \frac{\partial \mathbf{g}}{\partial \mathbf{x}}\Delta\mathbf{x} + \frac{\partial \mathbf{g}}{\partial \mathbf{v}}\Delta\mathbf{v} + \frac{\partial \mathbf{g}}{\partial \mathbf{q}}\Delta\mathbf{q} \\
\Delta\mathbf{y} &= \frac{\partial \mathbf{h}}{\partial \mathbf{x}}\Delta\mathbf{x} + \frac{\partial \mathbf{h}}{\partial \mathbf{v}}\Delta\mathbf{v}
\end{aligned} \tag{2-2}$$

or

$$\begin{aligned}
\frac{\mathbf{d}(\Delta\mathbf{x})}{\mathbf{dt}} &= \mathbf{A}_q\Delta\mathbf{x} + \mathbf{B}_{qv}\Delta\mathbf{v} + \mathbf{B}_{qq}\Delta\mathbf{q} \\
\mathbf{0} &= \mathbf{C}_q\Delta\mathbf{x} + \mathbf{Y}_n\Delta\mathbf{v} + \mathbf{Z}_q\Delta\mathbf{q} \\
\Delta\mathbf{y} &= \mathbf{C}_o\Delta\mathbf{x} + \mathbf{K}_o\Delta\mathbf{v}
\end{aligned} \tag{2-3}$$

Linearized equations, such as these, are the starting point of all power system modal analysis. The algebraic equations can be eliminated to give the system's state equations:

$$\begin{aligned}
\frac{\mathbf{d}(\Delta\mathbf{x})}{\mathbf{dt}} &= \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{q} \\
\mathbf{y} &= \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{q}
\end{aligned} \tag{2-4}$$

with

$$\begin{aligned}
\mathbf{A} &= \mathbf{A}_q - \mathbf{B}_{qv}(\mathbf{Y}_n)^{-1}\mathbf{C}_q \\
\mathbf{B} &= \mathbf{B}_{qq} - \mathbf{B}_{qv}(\mathbf{Y}_n)^{-1}\mathbf{Z}_q \\
\mathbf{C} &= \mathbf{C}_o - \mathbf{K}_o(\mathbf{Y}_n)^{-1}\mathbf{C}_q \\
\mathbf{D} &= -\mathbf{K}_0(\mathbf{Y}_n)^{-1}\mathbf{Z}_q
\end{aligned} \tag{2-5}$$

2. Eigenvalue and Eigenvector

By taking the Laplace transform of Equation 2-4, the state equations in the frequency domain is obtained [35]:

$$s\Delta x(s) - \Delta x(0) = A\Delta x(s) + B\Delta q(s)$$
$$\Delta y(s) = C\Delta x(s) + D\Delta q(s) \tag{2-6}$$

By definition, the eigenvalues of matrix A are the values of λ for which

$$\det(A - \lambda I) = 0 \tag{2-7}$$

Equation 2-7 is referred to as the characteristic equation of matrix A.

Associated with each eigenvalue λ_i are a right eigenvector φ_i and a left eigenvector ψ_i which satisfy

$$A\varphi_i = \lambda_i \varphi_i \text{ and } \psi_i A = \psi_i \lambda_i \tag{2-8}$$

From the above definition, it follows that if the eigenvalues are distinct then the left and right eigenvectors corresponding to different eignevalues are orthogonal, i.e.

$$\psi_j \varphi_i = 0 \text{ for } i \neq j$$
$$\psi_j \varphi_i \neq 0 \text{ for } i = j \tag{2-9}$$

Normally the eigenvectors are scaled to make

$$\psi_j \varphi_i = 1 \text{ for } i = j \tag{2-10}$$

In that case,

$$\varphi\psi = I \tag{2-11}$$

where the column of the matrix φ is all the right eigenvectors φ_i, and matrix ψ is all the left eigenvectors ψ_i. Using φ, consider a new state vector z related to the original state vector Δx, the state variables can be transformed as follows:

$$\Delta x = \varphi z \tag{2-12}$$

The free motion (with zero input) of the state equation 2-4 is given by

$$\frac{d(\Delta x)}{dt} = A\Delta x \tag{2-13}$$

Substitute Equation 2-12 into Equation 2-13 yields

$$\varphi \frac{dz}{dt} = A\varphi z \tag{2-14}$$

The new state equation can be written as

$$\frac{\mathbf{dz}}{\mathbf{dt}} = \boldsymbol{\varphi}^{-1}\mathbf{A}\boldsymbol{\varphi}\mathbf{z} \tag{2-15}$$

$\boldsymbol{\varphi}^{-1}\mathbf{A}\boldsymbol{\varphi}$ is a diagonal matrix ($\boldsymbol{\Lambda}$), which contains the eigenvalues of the system, and therefore the above equation becomes

$$\frac{\mathbf{dz}}{\mathbf{dt}} = \boldsymbol{\Lambda}\mathbf{z} \tag{2-16}$$

3. Eigenvalue and Stability

Since $\boldsymbol{\Lambda}$ is diagonal, the dynamic equations are decoupled and may be solved separately. The general solution of the i^{th} equation is

$$z_i(t) = z_i(0)e^{\lambda_i t} \tag{2-17}$$

where $z_i(0)$ is the initial value of z_i.

Since

$$\mathbf{\Delta x(t)} = \boldsymbol{\varphi}\mathbf{z(t)} \tag{2-18}$$

$$\mathbf{\Delta x(t)} = \sum_{i=1}^{n} \boldsymbol{\varphi}_i z_i(0)e^{\lambda_i t} \tag{2-19}$$

With an initial condition of the state vector $\mathbf{\Delta x(0)}$,

$$\mathbf{z(0)} = \boldsymbol{\varphi}^{-1}\mathbf{\Delta x(0)} = \boldsymbol{\psi}\mathbf{\Delta x(0)} \tag{2-20}$$

Hence,

$$\mathbf{\Delta x(t)} = \sum_{i=1}^{n} \boldsymbol{\varphi}_i \boldsymbol{\psi}_i \mathbf{\Delta x(0)} e^{\lambda_i t} = \sum_{i=1}^{n} u_i e^{\lambda_i t} \tag{2-21}$$

Each component of this sum $\Delta x_i = u_i e^{\lambda_i t}$ is called a mode of the system. The number of modes is equal to the number of states. The vector u_i is called an eigenvector. The eigenvalue λ_i may be real or complex. The time response characteristic of a mode corresponding to an eigenvalue λ_i is given by $e^{\lambda_i t}$. Therefore, the stability of the system is determined by the eigenvalues as follows [35]:

- A real eigenvalue corresponds to a non-oscillatory mode. A negative real eigenvalue represents a decaying mode. The larger its magnitude, the faster the decay. A positive real eigenvalue represents aperiodic instability.

- Complex eigenvalues always occur in conjugate pairs, and each pair corresponds to an oscillatory mode.

Complex eigenvalue can be represent with a general form $\sigma \pm j\omega$. Consequently, the corresponding oscillatory mode has the form of $e^{\sigma t}\sin(\omega t + \theta)$, which represents a damped sinusoid for a negative σ. The imaginary component of the eigenvalue, ω, determines the frequency of oscillation. The frequency in Hz can be computed by $\frac{\omega}{2\pi}$. The real part of the eigenvalue, σ, determines the stability of the mode. If σ is negative, then the amplitude of mode decays with time and is stable. If σ is positive, the amplitude of the mode increases with time and the system is unstable. When σ is zero, the mode will oscillate with a constant amplitude. So, in eigenvalue analysis, the system stability is evaluated by determining whether all eigenvalues have negative real part. If any eigenvalue has a positive or zero real part, the system is unstable [6].

The damping ratio (ζ) of an oscillatory mode is defined as:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \cdot 100\% \tag{2-22}$$

Since the damping ratio determines the decay rate of the amplitude of the oscillation, it is a quantitative measure of the degree of system damping. To get a desirable system performance, each oscillation mode need satisfy some damping requirement. The graphical presentation for an oscillation mode with eigenvalue of $\lambda = -0.315 + j6.28$ and damping of 5% is shown in Figure 2.1 and Figure 2.2.

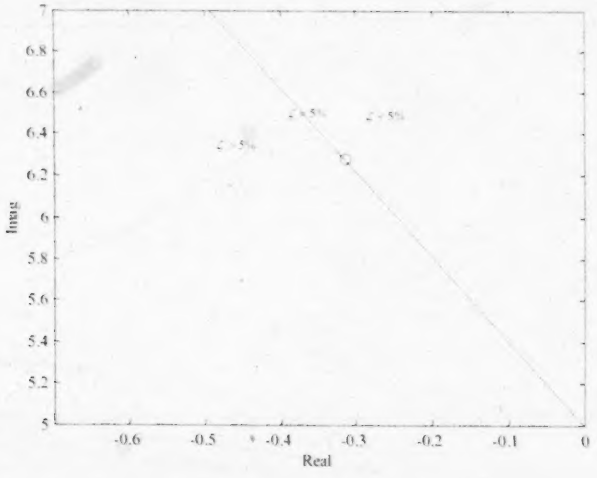


Figure 2.1 Eigenvalue location of an oscillation mode with 5% damping

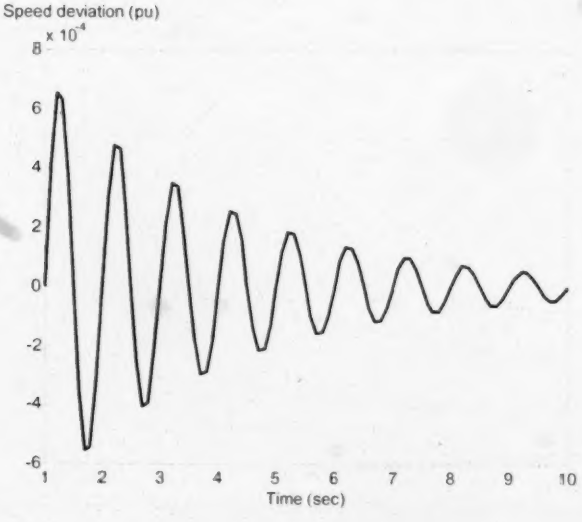


Figure 2.2 Time-domain simulation of an oscillation mode with 5% damping

Thus, the eigenvalues of the system are indicative of system performance. The real part is a measure of the amount of damping. The imaginary part is related to the damped natural frequency of the corresponding oscillation mode. This close relationship between mathematical results and the physical system is very useful in determining how to improve inadequate damping.

4. Participation Factor

From Equation 2-11 and 2-12, state vectors Δx and z have the following relationship.

$$\Delta x(t) = \phi z(t) = [\phi_1 \phi_2 \ldots \phi_n] z(t) \tag{2-23}$$

$$z(t) = \varphi \Delta x(t) = \left[\varphi_1^T \varphi_2^T \ldots \varphi_n^T\right]^T \Delta x(t) \tag{2-24}$$

From Equation 2-23, we see that the right eigenvector ϕ_i describes the relative activity of the state variables when a particular mode is excited; it is often called mode shape. As seen from Equation 2-24, the left eigenvector φ_i identifies which combination of the original state variables displays only the ith mode. Therefore, right eigenvector associated with a mode defines the relative distribution of the mode throughout the system's dynamic states. While left eigenvector can be interpreted as giving the contribution of the states within a mode.

However, one problem in using right and left eigenvectors individually for identifying the relationship between the states and the modes is that the elements of the eigenvectors are dependent on units and scaling associated with the state variables. As a solution to this problem, a matrix called the participation factor (P) is defined as a measure of the association between the state variables and the modes. For the ith mode, each element p_{ki} of P is the element multiplication of the right and left eigenvector, which is shown as follows [35],

$$p_{ki} = \phi_{ki} \varphi_{ik} \tag{2-25}$$

with

$$\sum_{i=1}^{n} p_{ki} = 1 \tag{2-26}$$

As a result, p_{ki} is a measure of the relative participation of the k th state variable in the i th mode, and vice versa. p_{ki} is also equal to the sensitivity of the eigenvalue λ_i to the diagonal element a_{kk} of the state matrix A. The participation factors are generally indicative of the relative participations of the respective states in the corresponding modes.

From above description, it is found that modal analysis based on eigenvalue technique is well suited for analyzing problems associated with damping oscillations. The strength of this method is [35]:

1. All modes are clearly separated and identified by the corresponding eigenvalues.

2. Mode shapes and the relationships between different modes and system variables or parameters are easily identified using eigenvector or participation factors.

3. Frequency response, poles and zeros, and residues can be easily computed.

2.1.2.2 Analysis Method of Power System Oscillations

System oscillation problems are often investigated using nonlinear time-domain simulations as an extension to transient stability analysis. However, there are a number of practical problems that limit the effectiveness of this approach [9]:

1) The use of time response for the analysis of damping for different modes of oscillations could be deceptive. The choice of disturbance and the selection of variables for observing time response are critical. The disturbance may not provide sufficient excitation of the critical modes. The observed response contain many modes, and poorly damped modes may not be dominant.

2) To get a clear indication of growing oscillations, it is necessary to carry the simulations lengthy. This could be time-consuming.

3) Direct inspection of time response does not give sufficient insight into the nature of the oscillatory stability problem; it is difficult to identify the sources of the problem and develop corrective measures.

Thus, only use of the time-domain simulation is not sufficient to investigate oscillation problems.

Compared with the time-domain simulations, modal analysis based on eigenvalue techniques is better suited for investigating problems associated with oscillations. With eigenvalue techniques, all modes are clearly defined and the lightly damped modes are easily identified. Especially, root locus conditions provide valuable insight into the dynamic characteristics of the system. The eigenvectors give an indication of the relative magnitudes of and phase displacements between different modes existing in any system variable [33]. Therefore, modal analysis is used to resolve the nature of oscillations, to locate the devices participation in the oscillations, and to provide the information required to design a controller, or determine the correct setting for an existing control.

However, after a solution is obtained using modal analysis, the performance of system should be checked by nonlinear time-domain simulation to verify the effectiveness of the solution.

Generally, modal analysis complemented by nonlinear time-domain simulation is the most effective way of studying power system oscillations. A recommended study procedure was provided in Reference 9. The following are the steps to be followed for a systematic analysis:

1. Eigenvalue scan using a small-signal stability program. This will indicate the presence of the poorly damped modes.

2. A detailed modal analysis of the poorly damped modes. This will determine their characteristics and sources, and assist in developing mitigation measures.

3. Time-domain simulation of the critical cases. This is useful to confirm the results of modal analysis. In addition, it shows how system nonlinearities affect the oscillations.

4. Time-domain simulation of results verification for controller design.

2.2 Power System Stabilizer (PSS)

Beginning in the late 1950's and early 1960's, most of the new generating units added to electric utility systems were equipped with continuously-acting voltage regulators. As these units became a larger percentage of the generating capacity, it became apparent that the voltage regulator action had a detrimental impact upon the dynamic stability of the power system. Oscillations of small magnitude and low frequency often persisted for long periods of time and in some cases limited power transfer capability. Consequently, PSS has been developed to aid in damping these oscillations via modulation of the generator excitation [35].

As it has been noted in Chapter 1, for mitigation of power system oscillations, using PSS as a damping control is more cost-effective than adding modulation controllers or additional devices such as SVC, HVDC or FACTS [9]. Since the first introduction, PSS has proved to be a very attractive and generally accepted solution to the electromechanical oscillation problem. It has been widely used to successfully damp system oscillation modes of various frequencies over a range of operating conditions.

The general concept of PSS associated with applying different input signals is described in the following part.

2.2.1 Theoretical Basis of PSS

The basic function of PSS is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal(s). To provide damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviation [35]. The theoretical basis for a PSS may be illustrated with the aid of the block diagram shown in Figure 2.3.

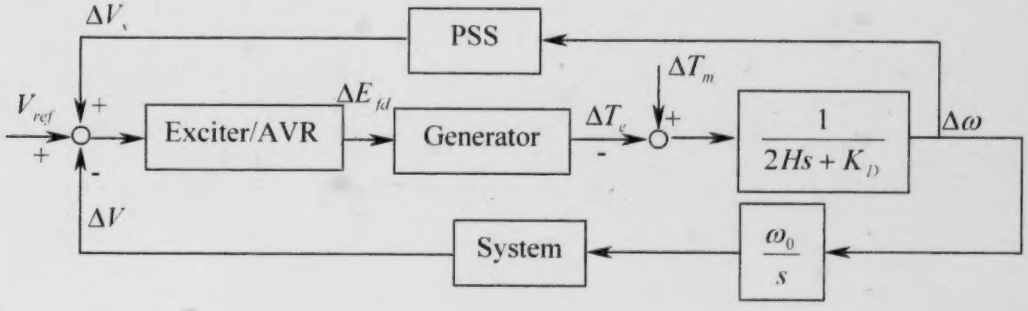


Figure 2.3 Block diagram of PSS application

PSS is to provide an additional input signal to AVR to damp power system oscillations. Commonly used input signals to PSS are shaft speed, terminal frequency and power. Since the purpose of a PSS is to introduce a damping torque component, according to Equation 1-1, it is logical to use the speed deviation $\Delta\omega$ as the input signal to control the generator excitation. In the ideal case, with the phase characteristic of PSS being an exact inverse of the exciter and generator phase characteristics to be compensated, the PSS would result in a pure damping torque at all oscillation frequencies [35].

In Figure 2.3, if the exciter/AVR transfer function and the generator transfer function from ΔE_{fd} to ΔT_e were pure gains, a direct feedback of $\Delta\omega$ would result in a damping torque component. However, in practice, both the generator and the exciter exhibit frequency dependant gain and phase characteristics. Therefore, the PSS transfer function should have appropriate phase correction to compensate for the phase lag between the exciter input V_{ref} and the electrical torque ΔT_e. The amount of phase compensation required is collectively determined by the characteristics of the excitation system, the generator, and the power system. It can be obtained by analysis of the frequency response of ΔT_e under injection of a disturbance in the exciter input V_{ref}.

To be robust enough, the PSS compensation should be matched in a wide frequency range and damping should be provided even if the oscillation mode changes.

2.2.2 PSS Type and Characteristics

PSS can be classified into the following four types according to different input signals.

a) Speed input stabilizer

PSS based on shaft speed signal has been used successfully on hydraulic units since the mid of 1960s. However, speed input PSS has the following inherent limitations, which can restrict the range of its application [12]:

1. Speed input stabilizer can contribute negative damping of shaft torsional modes of oscillation. Thus, special speed sensing arrangements should be used with speed input stabilizers to ensure that the torsional modes cannot be excited.

2. A torsional filter is employed as an added precaution against the possibility of torsional excitation [40].

3. The use of torsional filter invariably produces some phase lag in the stabilizing path. This has the effect of reducing the maximum usable stabilizer gain.

4. The stabilizer has to be custom-designed for each type of generating unit depending on its torsional characteristics [35].

b) Power input stabilizer

The presence of the noise components in the input of a speed-based stabilizer can result in excessive modulation of the generator's excitation and, for the case of torsional components, in the production of potentially damaging electrical torque variations. These electrical torque variations led to the investigation of stabilizer designs based upon measured power [15], [22], [36].

For small deviations in rotor speed, the difference between the mechanical and the electrical torque are approximately equal to the respective per unit power values. When disturbed from the equilibrium, the rotor accelerates at a rate that is proportional to the net torque acting on the rotor divided by the machine's inertia constant. Principal operation of power input stabilizer is based on this fact, which is represent by the following equation,

$$\Delta\omega_{eq} = \Delta P_a \cdot \frac{1}{2Hs} = (P_m - P_e) \cdot \frac{1}{2Hs} \tag{2-27}$$

where

$\Delta\omega_{eq}$ is the derived or equivalent speed deviation,

ΔP_a is the accelerating power,

H is the inertia constant of generator,

P_m is the mechanical power,

P_e is the electrical power.

Thus, according to Equation 2-27, when the input of PSS is power, either P_e or ΔP_a, it needs to be converted into an equivalent speed input $\Delta\omega_{eq}$ by using an integrator. In some cases, an additional integrator is not provided for this type of PSS, which can be replaced by a lag block with the following transfer function

$$F(s)=\frac{T_w}{1+sT_w} \tag{2-28}$$

Rewrite Equation 2-28 as the following form.

$$F(s)=\frac{sT_w}{1+sT_w}\cdot\frac{1}{s} \tag{2-29}$$

Then this lag block includes two components, a washout $sT_w/(1+sT_w)$ and an integrator $1/s$. The washout is to eliminate the dc component or reduce the close-to-dc component of the measured signal and has a large time constant T_w [35].

The power input stabilizer does not cause instability of the torsional modes. However, a major problem with power input PSS is that the terminal voltage of generator varies with the slow ramping of the generator's output power when changing load on unit or other system conditions. Another practical disadvantage is the risk of saturating the PSS output when the generator is ramping-up power, with the consequent loss of oscillation damping action. Thus, the use of power as the input signal to the stabilizer, despite its simplicity, has been mostly abandoned due to its comparatively poor performance [17].

c) Frequency input stabilizer

Bus frequency deviation can be used directly as the input signal of stabilizer because it is close to rotor speed deviation. Although widely applied, the frequency-based stabilizer suffers from several shortcomings [16], [35]:

1. Frequency signals measured at the terminals of thermal units contain torsional components. Hence, it is necessary to filter torsional modes when used with steam turbine units. In this respect, frequency-based stabilizers have the same limitations as the speed input stabilizer.

2. Phase shifts in the ac voltage resulting from changes in power system configuration, produce large frequency transients that are then transferred to the generator's field voltage and output quantities.

3. The frequency signal often contains power system noise caused by large industrial loads such as arc frnaces.

4. The terminal frequency quantity has a lower content of local modes relative to inter-area modes. Depending on the application, this may be desirable, but it can result in inadequate contribution to the damping of modes that only involve individual machines.

In many cases, these shortcomings have prevented the use of frequency as input signal of PSS.

d) $\Delta P / \omega$ Stabilizer

To overcome the problems result in from using a single input signal alone with above PSS, a derived $\Delta P / \omega$ PSS using dual input signals - electrical power and speed has been introduced.

The principle of this stabilizer is illustrated by the fundamental relationship among mechanical power, electrical power, accelerating power and speed of generating unit, which is shown in Figure 2.4.

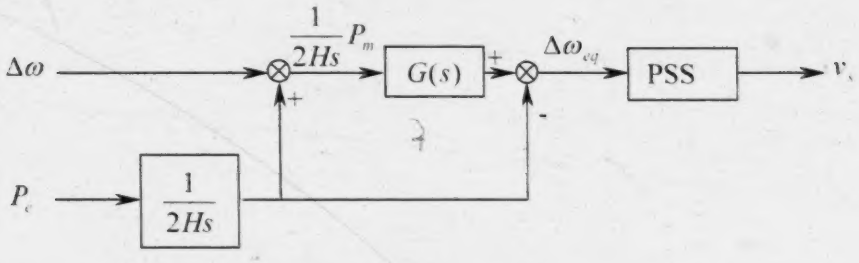


Figure 2.4 Block diagram of $\Delta P/\omega$ stabilizer

The operation of this stabilizer is based on applying signal conditioning to a measured electrical power and speed input signal so that they can be combined to derive a signal proportional to the mechanical power of the unit. which is shown in the following equation.

$$\frac{1}{2Hs}\cdot P_m = \Delta\omega + \frac{1}{2Hs}P_e \tag{2-30}$$

Normally, mechanical power changes are quite slow relative to the electromechanical oscillations of interest. Because of this, the derived mechanical power signal from Equation 2-30 can be band-limited using a low-pass filter $G(s)$ without affecting the behavior of its output signal for normal variations. Such filtering serves to remove the unwanted higher frequencies associated with measurement noise or torsional frequencies of oscillation from the speed input signal $\Delta\omega$. Thus the input shaft speed signal does not need to be separately processed to remove torsional components. Since it passes through the mechanical power low-pass filter $G(s)$, when signal is combined with the integrated electrical power signal $\frac{1}{2Hs}P_e$, it still produces a valid accelerating power and derived an equivalent speed signal $\Delta\omega_{eq}$, which can be derived from Equation 2-27.

The resulting output $\Delta\omega_{eq}$ can now be treated as a direct shaft speed measurement. With phase compensator, adjustable gain, and signal limiting are applied to produce the final PSS output [16]. Stabilizers utilizing this approach can normally be set to much higher gains than speed or frequency-based designs and are therefore much more effective in stabilizing the generator.

Thus, the primary advantages of $\Delta P/\omega$ Stabilizer are:

1. The power input has a high degree of torsional attenuation, and hence no torsional filter is needed in the main stabilizer path. This eliminates the exciter mode stability problem and therefore permits a higher stabilizer gain that results in better damping of electromechanical oscillations. Therefore it is almost torsional mode free over a lager frequency range.

2. A special low pass filter is placed before the stabilizer main path. The filter causes the effective stabilizer input to be speed at low frequencies and proportional to the integral of power at high frequencies. Then, the equivalent input becomes a filtered speed signal over the whole frequency range. Thus, it does not respond adversely to slow ramping of the generator power, and it is almost not affected by the variation of generator's output power.

3. The shaft location for speed sensing is not critical.

The model described above can be illustrated by the block diagram shown in Figure 2.5. In Figure 2.5, the steady-state components of both speed deviation and electrical power signals are removed by two high pass or "washout" filters. Torsional components in the electrical power path are already inherently attenuated. Two filtered signals are added to form the derived integral of change in mechanical power component. Then, this combined signal is processed by a low-pass filter and the ramp-tracking filter,

the purpose of which is to improve the quality of speed signal. One typical form of the ramp-tracking filter is

$$F(s) = \left(\frac{1 + sT_8}{(1 + sT_9)^m} \right)^n \tag{2-31}$$

where T_9, m and n are selected to produce the required attenuation of higher frequency components appearing in the speed signal, and T_8 is selected to provide the desired ramp-tracking behavior, using the following relationship:

$$T_8 = m * T_9 \tag{2-32}$$

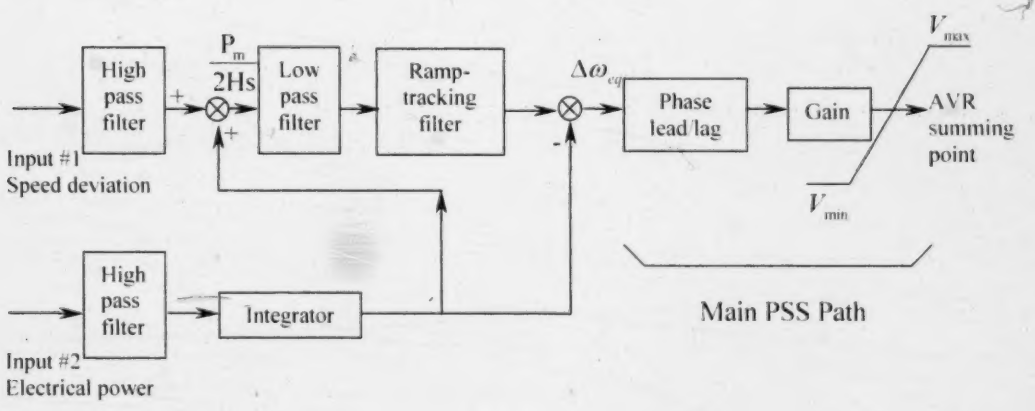


Figure 2.5 Dual-input power system stabilizer

With this design, the filtered integral of mechanical power signal can track rapid rates of change in the measured electrical power signal, greatly reducing the terminal voltage modulation produced by the PSS [16]. Signal after the ramp-tracking filter is combined with the integrated electrical power to produce equivalent speed $\Delta\omega_{eq}$, which is derived as the input signal to the main path of PSS. And the terminal voltage limiter signal is added before the summing junction of AVR. The purpose is to allow large excursion of the stabilizing signal in the positive direction, but prevent excessive terminal voltage as a result of stabilizer malfunction.

Therefore, the $\Delta P/\omega$ stabilizer removes many of the limitations inherent in the use of either signal separately, and it is widely used in industry.

2.2.3 General Considération of PSS Parameter Determination

To enhance the reliable operation of power systems, generally, the designed/tuned PSS must satisfy the following basic requirements and objectives [16]:

1. A high degree of functional reliability: the PSS should operate as expected with a high degree of reliability when any component fails.

2. Enhancement of the overall power system dynamic performance: the PSS should contribute to the damping of electro-mechanical modes of oscillation, without adversely affecting other aspects of system performance.

3. Robustness of control design: the PSS should perform as intended over the range of operating conditions that the power system is likely to experience.

4. Coordination with other controls and protections: The design and tuning of PSS should be coordinated with those of other controls and protective systems so as to have no adverse interaction with them. As far as possible, the PSS should complement other controls in enhancing the power system performance.

For the consideration of utility application, this thesis only focuses on the conventional PSS for design/tuning. The conventional PSS are basically linear controllers with fixed parameters, which are characterized as non-adaptive. The most commonly used input signals for conventional PSS include rotor speed, bus frequency, electrical power, or their combinations.

Other types of PSS in research include some PSS configuration based on nonlinear theory such as self-tuning or adaptive PSS [21], [47], [48], [50]. They are designed/tuned in such a way that a satisfactory control results for a wide range of operating conditions is to be achieved by tracking the random changes in the operating conditions of power system. At present, nonlinear PSS are not widely used in real power systems due to the difficulties in implementation, complexity of the design/tuning theory and general reluctance to implement new and unproven designs.

In contrast to the nonlinear PSS, conventional PSS are widely used in power system at present. The theoretical foundation and design methodology of conventional PSS, and field-testing procedure have been developed by many applications. Industry-accepted procedures for PSS design and tuning have been established. The simple structure of conventional PSS also makes the implementation easy.

The typical structure of a conventional PSS is shown in Figure 2.6. It mainly consists of a washout, a gain, a limiter, and two or three stages of compensation blocks, normally in the form of first order lead/lag block. The PSS uses the lead/lag function to provide the required phase compensation. The output of PSS is added to the AVR input summing junction. The filter block is not always necessary.

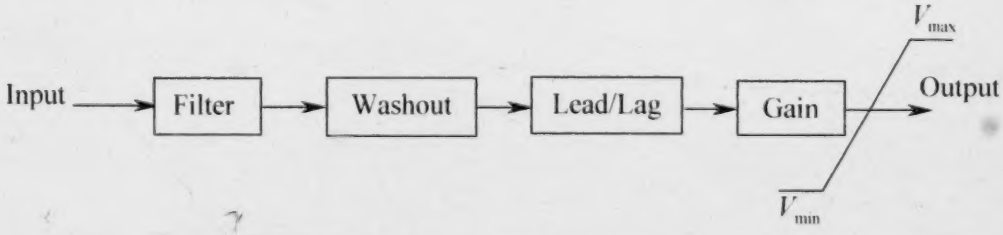


Figure 2.6 Block diagram of a conventional PSS

Based on the structure of conventional PSS, there are some general considerations for PSS parameter determination to enhance the overall stability of power systems [35].

a) Phase-lead compensation:

The required phase-lead of PSS is to compensate the phase lag between the exciter input (i.e. PSS output) and the resulting electrical torque.

PSS is often required to enhance damping of either a local mode or an inter-area mode of oscillation. The phase compensation should contribute to damping of both oscillation modes.

The phase characteristic to be compensated is obtained from the frequency response, which varies to some extent with system conditions. Therefore, a phase characteristic acceptable for different system conditions is selected. Slight under-compensation is preferable to overcompensation so that both damping and synchronizing torque components are increased. Generally, an under-compensation by about 10 degrees over the entire frequency range of interest provides the required tolerance to allow of uncertainties in machine and system modeling [9].

b) Stabilizing signal washout:

The physical implementation of the washout block is represented by the function shown in the following form

$$F(s) = \frac{sT_w}{1+sT_w} \tag{2-33}$$

The purpose is to filter the DC component to eliminate steady state offset of the PSS output. Normally it is a high-pass filter. From the viewpoint of the "washout function", the value of T_w is not critical and may be anywhere in the range of 1 to 5 seconds. The main considerations are that T_w should be long enough to pass stabilizing signals at the frequencies of interest relatively unchanged, but not so long that it leads to

undesirable generator voltage excursions as a result of stabilizer action during system-islanding conditions.

Note that a relatively small T_w could increase phase lead of PSS in low frequencies. It may result in overcompensation in low frequencies, which will reduce the synchronizing torque component at inter-area frequencies. This desynchronizing effect is detrimental to inter-area transient stability, as it will cause the areas to swing farther apart following a disturbance.

c) Stabilizer gain:

The stabilizer gain has an important effect on damping of rotor oscillations. The value of the gain is chosen by examining the effect for a wide range of values. Ideally, the stabilizer gain should be set at a value corresponding to maximum damping. However, the gain is often limited by other considerations.

With a speed input stabilizer, the stability of the exciter mode becomes an overriding consideration restricting the use of high gain values as a result of the effect of the torsional filter. With a power input stabilizer, exciter mode stability is not a problem, and a considerably higher value of gain is acceptable. With a $\Delta P/\omega$ PSS, exciter mode stability is generally not a problem. A considerably higher value of gain is acceptable if the phase-lead compensation has been chosen to provide satisfactory phase characteristics over a range of frequencies. In such a case, the maximum value of the stabilizer gain is likely to be limited by practical considerations such as the effect on signal noise.

Stabilizer gain is normally set to a value that yields as high a damping of the critical system modes as practical without compromising the stability of other system modes or causing excessive amplification of signal noise. According to Reference [44], a gain margin larger than 6 dB can provide the desirable stability for most feedback control system. The detail of PSS gain tuning will be described in Chapter 3.

d) Stabilizer limits:

The output of a damping control must be limited to prevent it from saturating the device being modulated. Saturating a controlled device would defeat the purpose of the damping control. As a general rule for damping, when a control is at its limits in the frequency range of oscillations, the output of the controlled device should also be just within its respective limits [25].

The positive output limit of the stabilizer is set at a relatively large value in the range of 0.1 to 0.2 pu. This allows a high level of contribution from the PSS during large swings. With such a high value of stabilizer output limit, it is essential to have a means of limiting the generator terminal voltage to its maximum allowable value, typically in the 1.12 to 1.15 pu range. The negative output limit of the stabilizer in the range of –0.05 to –0.1 pu is appropriate. This allows sufficient control range while providing satisfactory transient response.

e) Filter:

The filter is designed to have as small effects as possible at the frequency range of the rotor angle mode. However, it does add some gain/phase lag to the phase compensation. The filter block is only necessary for some certain type of PSS.

2.2.4 Power System Operation Criteria and Evaluation of PSS Performance

After setting stabilizer parameters, the final stage is the evaluation of the effect of designed/tuned stabilizer on the overall system performance [16]. Extensive small and large signal stability verification under various operating conditions and disturbances are an essential part of the stabilizer design/tuning.

First, the effect of the stabilizer on small-signal performance is verified. This includes analysis of the effects of the PSS on local modes, inter-area modes, and control modes. The stability of the systems with and without the new or tuned PSS should be examined. After checking the PSS under small perturbations, it is also important to examine its effect on large-signal performance, i.e., the behavior of transient stability. Transient stability verification complemented the evaluation of small-signal performance, are needed to [1], [6]:

1. Confirm the results of the small signal stability analysis.

2. Study the stabilizer's impact on transient stability.

3. Study the effects of non-linearities on the performance of the stabilizer.

It is very important to chose an appropriate performance index or criteria not only for setting parameters of stabilizer, but also for verification of designed/tuned stabilizer. The IEEE standard [44] provides a basis for evaluating the closed-loop performance of excitation control systems for both large and small signal disturbances. It requires that both large and small signal performance criteria to be considered during design specification and performance verification.

2.2.4.1 Small-Signal Performance Criteria

Small-signal performance refers to the system's response to signals, which are small enough so that nonlinearities are insignificant. Small-signal performance can be assessed from time response, frequency response, or by eigenvalue analysis.

According to modal analysis technique, the damping ratio ζ (see Equation 2-22) is usually used as the criteria to assess the small-signal performance because it determines the decay rate of the oscillation amplitude. Based on this criteria, the system

should be designed and operated so that the following conditions are satisfied for all expected system conditions, including post-fault conditions following design contingencies:

1. The damping ratio of all modes of system oscillations should exceed a specified value. The minimum acceptable damping ratio is system dependent and is based on operating experience and sensitivity study. It is typically in range of 3% to 5%. For control modes, a damping ratio should normally be greater than 20%.

2. The small signal stability margin exceeds a specified value. Small-signal stability margin refers to the distance between a given operation condition and the critically stable condition (damping ratio $\zeta = 0$). This margin can be measured by a physical quantity such as a power plant output, power transfer at a critical transmission interface, or load level.

The small signal performance criteria can also be given based on the frequency response. Relative stability of a feedback control system is measured in terms of gain and phase margin. For most feedback control system, a gain margin larger than 6 dB and a phase margin larger than 40 degree is the desirable stability [44].

For the criteria based on time response, many utilities specify the maximum time or maximum number of swings within which amplitude of the least-damped system oscillation mode must decay to a specified level. Examples of such specification are: time constant of amplitude decay, halving time, and the time for damping down of the oscillations [9].

Some recommended performance criteria based on utility experiences could be obtained from Reference 10. The criteria could be significant different among utilities in the way of providing damping of oscillation.

2.2.4.2 Large-Signal Performance Criteria

Large signal performance refers to system's response to signals that are large enough so that nonlinearities are significant. The purpose of the large signal performance criteria is to provide a means of evaluating system performance for severe transients that may include large variations in the system, that is, for transients affecting the system transient stability. Time domain simulations are carried out to do the verification.

The criteria used for assessing the large signal performance of excitation systems are quantities such as transient response, ceiling currents and voltages, voltage response times, and nominal responses derived from the time response [18].

For the verification of large-signal performance with transient disturbance of specified contingencies, the system should survive the first few swings after a major system disturbance with some degree of margin. The corresponding criteria can be the transient stability index such as the critical clearing time for a contingency or maximum generator rotor angle swings, transient voltage dip (magnitude and duration), minimum transient frequency, post-transient voltage deviation etc..

A typical transient response of a feedback control system is often used as the criterion to verify the PSS performance in time-domain, which is shown in the following figure. The principal characteristics of interest are the rise time, overshoot, and setting time.

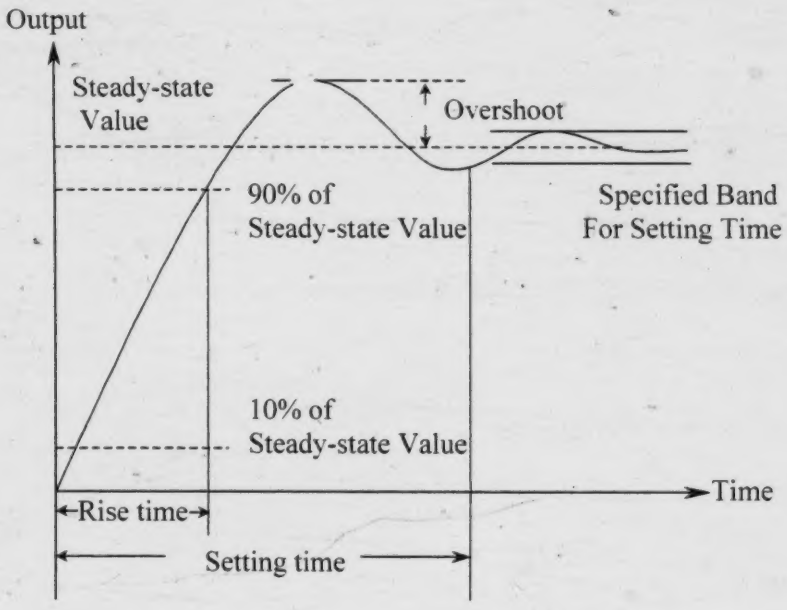


Figure 2.7 Typical transient response to a step change

- Rise time: The rise time is defined as the time required for the step response to rise from 10% to 90% of its final value.
- Maximum overshoot: The magnitude by which the step response overshoots the final setting value in percentage of the step input magnitude.
- Setting time: The setting time is defined as the time required for the step response to decrease and stay within a specified percentage of its final value.

2.2.4.3 Conclusion

Engineers from different countries have been reluctant to define universally applicable power system operation criteria [10]. Both the system design and operating criteria indicate that significant differences exist among utilities in the way of damping power system oscillations. So far, no universally applicable "best criteria" can be recommended.

In this project, we select the power system operation criteria that can be easily computed from the practical point of view. With this consideration, small-signal performance criteria based on eigenvalue analysis are used, e.g., the time constant of decay and damping ratio. One advantage of using the time constant of the amplitude decay is that it can be measured directly from time domain simulations used for transient stability analysis. However, the use of damping ratio may be more appropriate for indicating the degree of damping. This allows the criteria to be applied to a specific mode, rather than a range of modes. Of course, this damping ratio can easily be quantified in terms of a time constant of decay, but only for a specific modal frequency [9]. For large-signal performance criteria, indices of a typical transient response to a step change are used, which include rise time, setting time and overshoot. At the same time, the criteria for large disturbances can be defined by the user-specified contingencies.

2.3 Literature Review of the PSS Design/Tuning Methods

This section reviews some of the design/tuning methods that have been proposed for the conventional PSS. The review provides insight into some of the practical constraints that are imposed on PSS control strategies.

As mentioned in Section 2.2.3, in this project, only the conventional PSS, which have been generally accepted in industry are considered. Also, the implementation for PSS design/tuning will focus on conventional and proven methods that are widely used in industry. The intent is to make the design/tuning process practical and simple for large-scale power system models.

The following common PSS design/tuning techniques are briefly discussed:

- Pole placement technique
- Phase compensation and gain margin technique
- H-infinite control design technique

- Other methods

2.3.1 Pole Placement Technique [6]

Pole placement techniques use root locus to shift a pair of dominant poles to a newly assigned location in the s-plane. The proximity to instability can be defined by phase and gain margin between the plant open loop response and the $(-1+j0)$ point. These are used to design a compensator that meets the response specifications.

Let the transfer functions of the open-loop plant and the controller (compensator) be $G(s)$ and $H(s)$ respectively as shown in Figure 2.8. The closed-loop transfer function of the compensated plant is

$$G_c(s) = \frac{G(s)}{1+G(s)H(s)} \tag{2-34}$$

The zeros of $1+G(s)H(s)$, i.e., the roots of characteristic equation, are the poles of the closed-loop system.

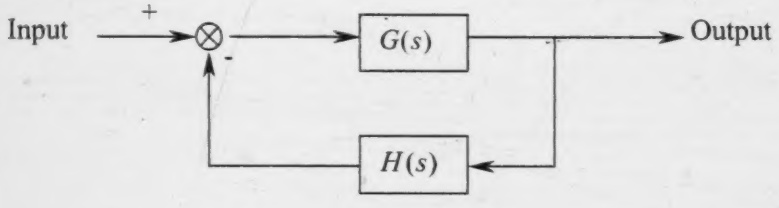


Figure 2.8 Plant with feedback

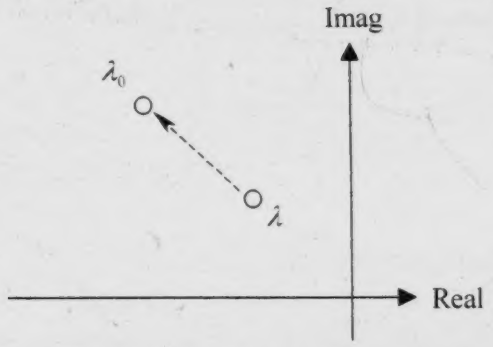


Figure 2.9 Eigenvalue location shifting

Assuming that an open-loop system eigenvalue, λ, is to be shifted to a new location in the s-plane denoted by λ_0, (see Figure 2.9). λ_0 must satisfy the characteristic equation of the closed-loop system. Hence,

$$H(\lambda_0) = \frac{-1}{G(\lambda_0)} \tag{2-35}$$

This can be written in terms of magnitude and phase as

$$|H(\lambda_0)| = \frac{1}{|G(\lambda_0)|} \tag{2-36}$$

$$\arg(H(\lambda_0)) = 180 - \arg(G(\lambda_0)) \tag{2-37}$$

Thus, the magnitude and phase of the controller at λ_0 can be calculated from the magnitude and phase of the plant at λ_0, based on the complex frequency response of the plant at the new pole location. The new pole location is chosen to satisfy the specified damping ratio.

The pole placement method provides a good graphical representation of the amount of damping that a particular controller is contributing to each of the mode considered. This approach gives additional insight to performance by working directly with the closed-loop characteristics of the system, as opposed to the open-loop characteristics. The pole placement method guarantees shift of an eigenvalue to a new

location, but does not guarantee that the poorly damped eigenvalue will shift to this new location. Thus, the pole placement method is not sufficiently robust for a wide range of conditions. To overcome these drawbacks, variation of the method based on optimal technique have been developed, such variations make the pole placement technique more feasible for PSS design in multi-machine system [19], [49].

2.3.2 Phase Compensation and Gain Margin Technique

With this method, phase of the controller is determined by phase compensation technique, and gain margin technique is used to determine the controller magnitude.

2.3.2.1 Phase Compensation Technique

Compensation is the process of modifying a closed-loop control system (usually by adding a compensator or controller) in such a way that the compensated system satisfies a given set of design specification [25].

In the diagram of the control system shown in Figure 2.8, the design procedures are normally based on the open-loop function of the uncompensated system $G(s)$. The phase to be compensated is obtained through frequency response of $G(s)$. Then parameters of compensator $H(s)$ are adjusted to compensate for the objective phase. In this design, the phase of compensator $H(s)$ can be phase lag or phase lead.

For the PSS design/tuning using phase compensation, the PSS phase should have an appropriate phase lead characteristic to compensate for the phase lag between the exciter input and the electrical torque (See Figure 2.3). Hence, a damping is provided by PSS through producing a component of electrical torque, which is in phase with the speed deviation.

To determine the objective phase to be compensated without the feedback effect of the rotor angle variations caused by change in electrical torque, the frequency response between the exciter input and generator electrical torque should be calculated assuming that the generator angle remains constant. For this reason, the electrical characteristics of the generating units under consideration are represented in detail as one equivalent unit with its inertia assumed to be very large (e.g., 1000 times the actual inertia). The dynamics of all other machines are neglected by representing them as infinite buses. This ensures that the effect of external machine is eliminated. The resulting phase characteristic has a relatively simple shape free from the effects of natural frequencies of the external machines [17]. The phase characteristics to be compensated change with system conditions. For a conventional PSS with fixed parameters, the optimum phase compensation cannot be achieved at all frequencies simultaneously. Therefore, a compromise must be made to achieve an acceptable phase compensation for a desired range of frequencies and different system conditions [34].

The phase compensation technique, which relies on frequency response to meet the system performance specifications, continues to dominate the PSS design/tuning strategies. This method provides insight into the controller response. The main advantage of this method is that it is very insensitive to changing system conditions and is not constrained by the size of system.

2.3.2.2 Gain Margin Technique

According to Nyquist stability criterion, gain margin is defined as the magnitude of $G(j\omega)$ at the phase crossover frequency, which is the frequency at which the phase angle of $G(j\omega)$ equals to -180^0. Gain margin is used to assess the relative stability of the closed-loop system. Thus, the function of the compensator $H(j\omega)$ is designed/tuned to provide enough gain margin for a particular mode, or modes so that the response specifications are met [6].

As described in Section 2.1.2.1, an oscillatory mode of $G(s)$ is unstable once its eigenvalue shifts to the right half of the s-plane with a positive real component. When stabilizer is designed as a compensator $H(s)$, the gain, which results in the unstable mode, is the margin value of the designed/tuned stabilizer. Typically, the maximum acceptable gain of stabilizer is set to about one-third of the gain margin [9].

For damping purpose, the stabilizer gain should be set to a value corresponding to maximum damping within the constraint of the gain margin. However, the gain is often limited by other considerations. Therefore, the main specification of gain is that it is set to a value, which results in satisfactory damping for a particular mode, or modes without unacceptable adverse effects on the other modes, and which does not cause excessive amplification of the stabilizer input signal noise.

2.3.3 H-Infinite Control Design Technique [6], [29]

A major requirement in control design is the robustness of the controller. For power system applications, this translates into the ability of the controller to perform satisfactorily under a broad range of operating conditions, and in the presence of other uncertainties such as disturbances and errors due to monitoring instruments. A control design method known as the H-infinite was developed to achieve this control objective [17].

H-infinite technique was first proposed by Zames in 1981. It is used as a frequency-domain technique to find optimum controllers, which implicitly reflect the response specification. It has been designed to have robustness properties. The H-infinite approach involves designing a feedback controller with the following objectives:

- To minimize the effect of disturbance in the plant output, subject to the constraint of the closed-loop stability.

- To realize a controller which will perform satisfactorily under a wide range of system operating conditions.

To formulate the problem for the H-infinite control design algorithm, the SISO system with plant $G(s)$ and controller $H(s)$ are arranged as shown in Figure 2.10. The system performance is specified in terms of three weighting functions $W_1(s)$, $W_2(s)$ and $W_3(s)$ associated with transfer functions specified as $S(s)$, $R(s)$ and $T(s)$, which are defined in the following equations:

$$S(s) = \frac{e}{u} = (I + G(s)H(s))^{-1} \tag{2-38}$$

$$R(s) = \frac{u_1}{u} = H(s)(I + G(s)H(s))^{-1} = H(s)S(s) \tag{2-39}$$

$$T(s) = \frac{y}{u} = G(s)H(s)(I + G(s)H(s))^{-1} = I - S(s) \tag{2-40}$$

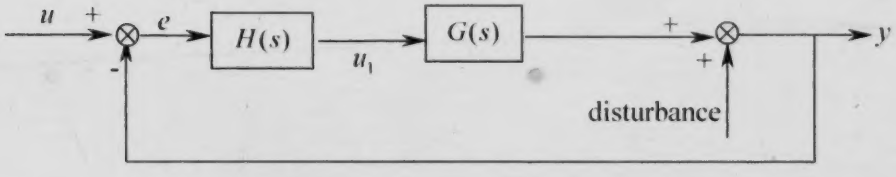


Figure 2.10 Perturbed plant with controller

$S(s)$ is also the closed-loop transfer function from the disturbance to the plant output y. Therefore, to minimize the effects of disturbance on the plant output, we specify

$$Max|S(j\omega)| \le |W_1^{-1}(j\omega)| \tag{2-41}$$

$|W_1^{-1}(j\omega)|$ defines the acceptable magnitude of error in the presence of disturbances. Since it is frequency dependent, a different error tolerance may be specified

for each frequency. Similarly, to guarantee stable performance of the controller in the presence of the plant modeling uncertainties, we add the following specifications:

$$Max|R(j\omega)| \le |W_2^{-1}(j\omega)| \tag{2-42}$$

$$Max|T(j\omega)| \le |W_3^{-1}(j\omega)| \tag{2-43}$$

Thus, the H-infinite algorithm yields an optimal controller that meets the following requirements:

$$\left\| \begin{matrix} W_1(jw)S(jw) \\ W_2(jw)R(jw) \\ W_3(jw)T(jw) \end{matrix} \right\| \le 1 \tag{2-44}$$

Clearly, the weighting functions are used to guide the H-infinite algorithm to generate a controller that meets the required performance specifications. This method makes the controller more robust for a broad range of operating conditions. However, the proper selection of the weighting functions is critical to the controller design.

As with all controllers designed by H-infinite technique, each controller has at least the same number of poles as the plant. It is thus important to use an adequate reduced order model in the design algorithm. Therefore, the success of an H-infinite controller design for a power system hinges to a large extent on the derivation of a high quality reduced system model and on the design specifications [17].

2.3.4 Other Methods

In addition to the above methods, there are a number of other methods for PSS design/tuning, which are based on nonlinear control theory. Most of them are still in the research stage and further work is required for their applications in industry. These methods are briefly described below:

1) Methods based on the state space

For a system with state space representation, state space feedback can be used to obtain a suitable closed-loop pole location. Several methods based on this theory have been applied in the design/tuning of PSS. These include full state feedback, a full order observer, output feedback, the projective method [11], as well as eigenstructure assignment by decentralized feedback control [8]. Of these methods, the last three methods emphasize the use of practical techniques rather than relying on the rigorous theory.

2) Optimal methods

In 1970's, optimal control theory was used for adjusting PSS parameters. The design theory for the linear optimal stabilizer is very simple. A linear optimal stabilizer can be formulated as a linear optimal regulator problem.

This approach, however, is not very practical when it is applied to a real power system model. The reasons are two-fold. On one side, the complexity of the theory and the difficulty in accessing state variables make it difficult to implement a PSS. On the other side, it is believed that the optimal controller does not perform well for wide operating ranges of generators. Some inherent drawbacks of this method, for example, the determination of proper weighting factors in the performance index, also make it less attractive.

To make the optimal method more practical, two alternative methods are developed: optimal reduced model method and sub optimal method [3], [7]. The idea is to consider only some measurable states in the optimization formulation. At the same time, since the number of eigenvalues that has to be dealt with in a multi-machine study is usually quite large, some reduction technique is used to reduce the order of the system. These two methods are more feasible than full state feedback technique. However, they

are arbitrary to some extent by only utilizing desired and/or available state variables. Moreover, the implementation can be impractical because of the high order or multi-feedback paths required for the designed/tuned PSS.

3) Nonlinear intelligent method

Several intelligent approaches based on modern control theory have been applied to PSS design/tuning problem. These include adaptive and genetic algorithms [5], variable structure and intelligent control [50]. Self-tuning or adaptive controllers have been obtained based on these methods [21], [26], [32].

However, these techniques require a large amount of time-consuming computation, and in most cases they are too impractical to be implemented.

2.3.5 Comments

In this section, a number of PSS design/tuning methods have been introduced and commented. Based on this, the proposed method for PSS design/tuning in this project is determined.

The pole placement method can be readily applied to increase the damping of a given system mode when only one system condition is of interest and the power system model is known accurately. However, the disadvantage is that it often results in parameters outside of practical ranges. There is no direct way of identifying a set of parameters suitable for widely differing system conditions. Also, the pole placement method becomes complex when dealing with oscillations associated with large system. For the designed/tuned PSS based on this technique, the adverse effects on other modes can be only checked after the initial design, and possibly reduced by trial and error. Moreover, assigning poles can be a task that is difficult to automate.

For H-infinite method, the difficulty associated with the choice of weighting functions limits the usefulness of this technique for PSS design/tuning [24]. In addition, the additive and/or multiplicative uncertainty representation cannot treat situations where a nominally stable system becomes unstable after being perturbed. On the other hand, the order of the H-infinite based stabilizer is as high as that of the plant. This gives rise to a complex structure of such stabilizers and reduces their applicability [20]. Also, in this application, the poorly damped pole-zero cancellations are problematic [26].

For methods based on the state space techniques, from a practical point of view, a full state feedback is undesirable [11]. This is obvious when considering high order systems and the cost of measuring and feeding back each state variable. The PSS design based on state space is satisfactory only for the oscillation associated with the system condition considered and may be unsatisfactory at other oscillation modes. Therefore it cannot deal with large complex systems and changing system conditions.

For the intelligent method based on genetic algorithm, there exist some structural problems, e.g. the premature processing. For other intelligent methods, the design process may require a large amount of computations at each iteration. This gives rise to heavy computational burden and slow convergence [26].

Compared with the above methods, phase compensation combined with gain margin technique is the most straightforward approach, easily understood and implemented in the field, and the most widely used. The most important advantage of this method is that it is not constrained by the complexity and size of the power system. In practice, this classical method, which relies on lead/lag compensators to reduce system sensitivity to disturbances, has continued to dominate many areas of design mainly because of its simplicity. It is more suitable when two or more modes are to be controlled by the same compensator. With phase compensation techniques, the adverse effects of designed/tuned PSS on other modes can be taken into account right at the beginning. It is also proved that the resulting design is much more robust than can be achieved through

use of other methods such as pole placement techniques and multivariable state space techniques. In addition, this approach is based on frequency-domain technique, which has a wider appeal among engineers.

Therefore, phase compensation combined with gain margin technique is adapted to the approach for PSS design/tuning in this project.

2.4 Conclusion

In this chapter, the characteristics and analysis method of power system oscillations, PSS theoretical foundation and design/tuning methodology have been presented. This chapter lays the foundation for the implementation of the proposed PSS design/tuning approach.

Modal analysis is the fundamental theory for small signal stability analysis. Modal analysis complemented by nonlinear time-domain simulation is the most effective way of studying power system oscillations.

As the most cost-effective controls for oscillation problems, PSS of different types are discussed. The objective, performance criteria and verification for PSS design/tuning are analyzed.

By comparing several controller design methods, phase compensation combined with gain margin technique is chosen as the proposed method for PSS design/tuning in this project.

So, in this project, the following considerations are determined for the power system oscillation analysis and PSS design/tuning:

- Modal analysis is used for the power system oscillation analysis;

- Phase compensation combined with gain margin technique is applied to design/tune PSS;

- Damping ratio and step response criteria is chosen to individually evaluate the small-signal and large-signal performance of the designed/tuned PSS.

Chapter 3

Power System Stabilizer Toolbox

3.1 Introduction

The theoretical foundation and design/tuning methodology of PSS have been described in Chapter 2. This chapter will introduce the development of a toolbox that automates the PSS design/tuning procedure.

The goal of this project is to develop a PSS design/tuning toolbox. The basic approach is to utilize the design/tuning methods selected and specialized analysis tools, to integrate these into a single toolbox, which focuses on considerations for practical applications. The emphasis is that, with a production power system model and a straightforward design/tuning objective, this toolbox completes all necessary computation steps in a PSS design/tuning cycle to give optimally designed or tuned PSS parameters, as well as the corresponding performance evaluation. The proposed PSS design/tuning toolbox is an independent application that embodies an automatic PSS design/tuning procedure. It is an add-on product for the DSA Power Tools™ with built-in connections to Small Signal Analysis Tool and Transient Security Assessment Tool. The corresponding application is shown in Figure 3.1.

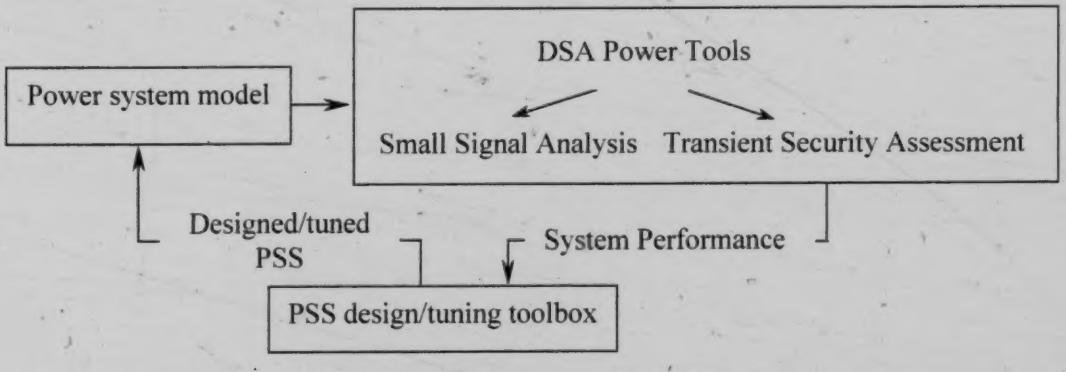


Figure 3.1 Diagram for application of PSS design/tuning toolbox

3.2 General Approach

3.2.1 PSS Design/Tuning Objective

In this project, two objectives are considered for PSS design/tuning:

- PSS design/tuning for the specific modes
- PSS design/tuning for the specific generators

Design/tuning of PSS for the specific modes is carried out to make a set of specific modes satisfy certain performance requirement. First, target modes to be considered are determined by small-signal analysis. Then the candidate generators that control these target modes are identified by some post computation analysis. Finally, PSS are optimally designed/tuned for these candidate generators. This procedure requires simultaneously design/tuning for multiple PSS.

Design/tuning PSS for the specific generators is carried out by computing the modes related to each specific generator individually. After identifying the dominant poorly damped modes for each specified generator, PSS is designed/tuned to make all poorly damped modes satisfy certain performance requirement. For this objective, PSS design/tuning is implemented sequentially.

Even though the procedures for these two objectives are isolated, to achieve an overall stability performance of power system, they should be coordinated so that no adverse effects on the other objective will occur when design/tuning PSS for one of them.

3.2.2 PSS Design/Tuning Parameters

As described in Section 2.2.3, a typical PSS consists of a filter, a washout, a lead/lag compensator, a gain and a limiter (See Figure 2.6). For different parameters of these blocks, there are different considerations when design/tuning PSS.

- Parameters determination focuses on the time constants of lead/lag compensator and gain because they have a significant effect on PSS behavior.

- Since time constants of washout are not critical for PSS behavior, they are acceptable once they belong to some reasonable band; otherwise, a default value is applied.

- Parameters of filter and limiter are not considered. The reason is that they are fixed once they are determined, and normally they do not have a major effect on PSS performance.

3.2.3 PSS Design/Tuning Procedure

Generally, PSS design/tuning involves the determination of appropriate settings for the adjustable PSS parameters such as time constants and gain. The main steps of the PSS design/tuning process are as follows [10]:

1) Determine the location of PSS to be designed/tuned.

2) Design/tune the PSS.

For this purpose, it is to determine the parameters of all target stabilizers to provide the best damping to a specific set of modes. This is typically a two-step problem:

- The lead/lag blocks of each selected stabilizer are designed to provide adequate phase compensation at the frequencies of modes of interest.

- The gains are determined to make the PSS design/tuning objective satisfy the performance requirement.

3) Obtain the small and large signal performance of the PSS in a full system model under various system conditions and disturbances. Thus the robustness of designed/tuned PSS is verified.

4) Ensure that no adverse interaction exists between the PSS, exciter, and control modes.

3.3 Consideration of PSS Types

In Chapter 2, different types of PSS are compared according to the input signals. This part will describe all types of PSS considered in this project, which focuses on those PSS widely used in the practical system models in North America.

There are two generalized forms for PSS considered in this project, the first refers to PSS with a single input signal, and the other type includes a variety of dual-input PSS. he input can be one of the signals of speed, frequency and power or their combination. The diagrams for PSS with a single input are shown on Figure 3.2 to Figure 3.5. The diagrams for PSS with dual-input signals are shown on Figure 3.6 to Figure 3.8.

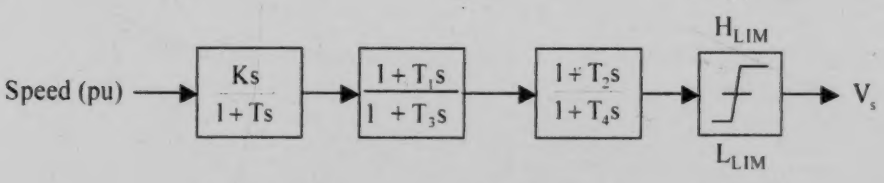


Figure 3.2 Block diagram of STAB1

With a speed input signal, STAB1 consists of a gain, a washout, two lead/lag blocks and a limiter.

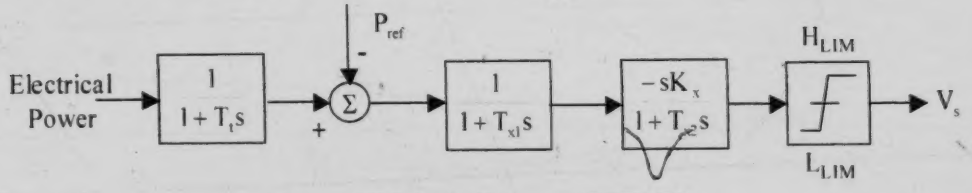


Figure 3.3 Block diagram of STAB3

With an electrical power input signal, STAB3 has a transducer, two washout blocks, a gain and a limiter.

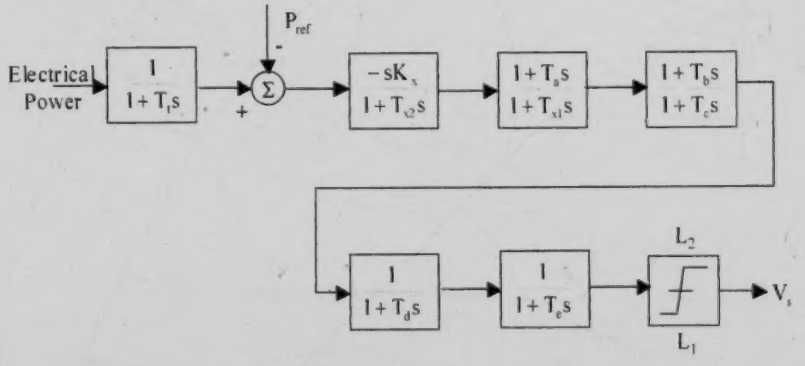


Figure 3.4 Block diagram of STAB4

STAB4 is similar to STAB3 except that it has several lead/lag blocks.

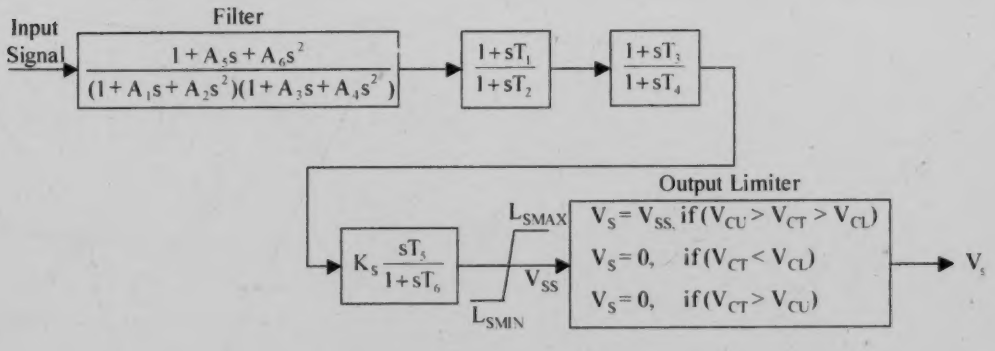


Figure 3.5 Block diagram of IEEEST

The input signal of IEEEST can be any of the signals of speed, frequency, or power. It has a filter, a washout, two lead/lag blocks, a gain and a limiter.

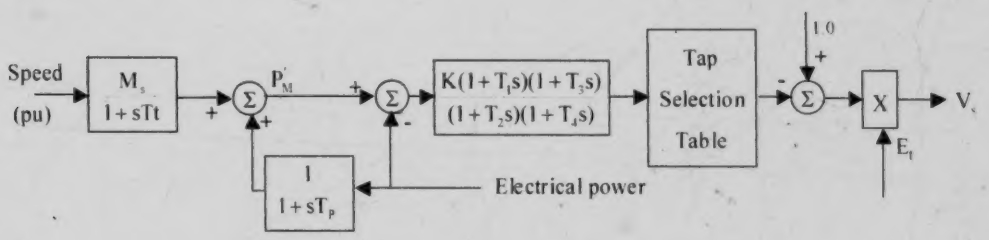


Figure 3.6 Block diagram of PTIST1

The dual-input signals of PTIST1 are the speed deviation and the electrical power. The main path of PSS includes a washout, two lead/lag blocks and a gain. The equivalent input signal to the main path of PTIST1 is accelerating power, which can be derived from Equation 2-30 and 2-18.

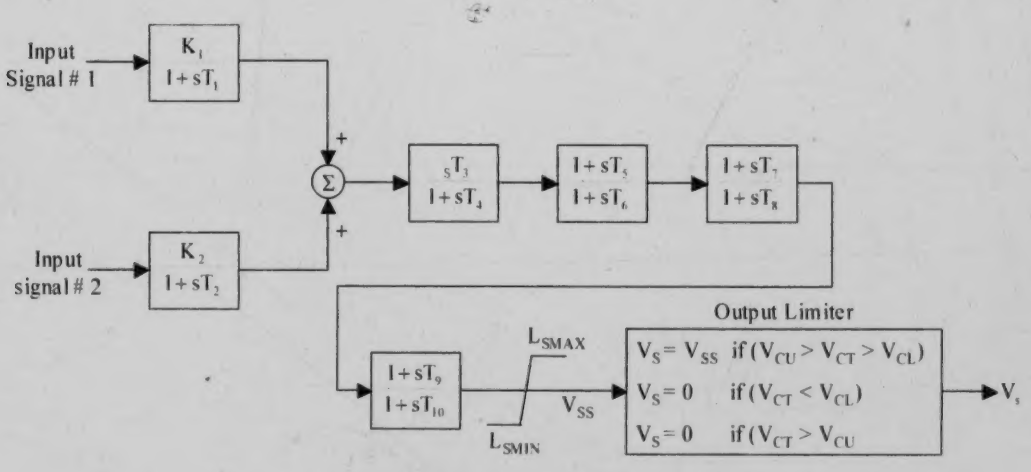


Figure 3.7 Block diagram of IEE2ST/ST2CUT

The input of IEEEST or ST2CUT can be any two combined signals of speed, frequency, or power. The main path of PSS includes two gains from two input signals, a washout, three lead/lag blocks and a limiter.

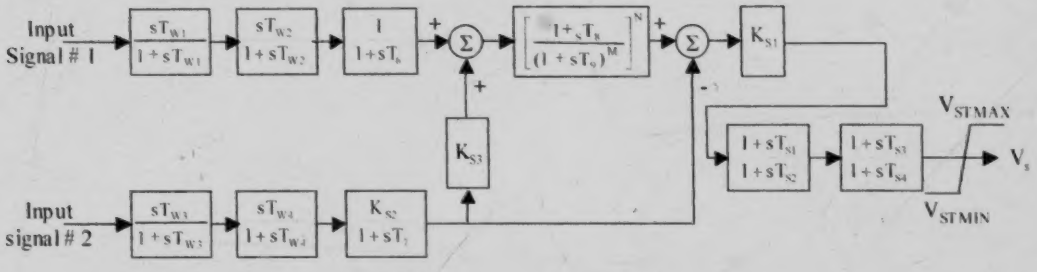


Figure 3.8 Block diagram of PSS2A

The input of PSS2A can be any two combined signals of speed, frequency, or power. The main path of PSS includes a gain and two lead/lag blocks. There is a ramp-tracking filter and several washouts before the main path of PSS.

Since the purpose of a PSS is to introduce a damping torque component, a logical signal used for PSS design/tuning is the speed deviation. Thus, for above types of PSS with power as input signal, should be converted into an equivalent PSS model, which is shown in Figure 3.9. The equivalent PSS includes all the components of a conventional PSS (see Figure 2.6) with the input signal of speed deviation $\Delta\omega$. The transformation between speed signal and power signal are based on Equation 2-27 in Section 2.2.1. Correspondingly, the gain to be determined is not necessarily the pure gain of original PSS, but rather than an equivalent gain represented as K_{eq} whose unit is pu change in torque/pu change in speed. Then, parameter determination of PSS will be carried out according to the structure of this equivalent PSS model.

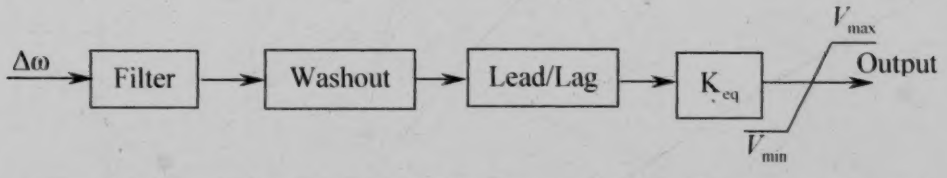


Figure 3.9 Equivalent PSS model with a rotor speed deviation as input signal

Based on structure of PSS shown in Figure 3.9, all block diagrams of the equivalent model for above types of PSS are shown on the following figures.

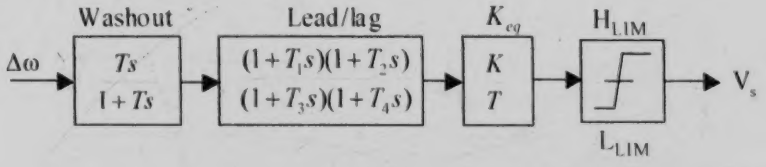


Figure 3.10 Equivalent PSS model of STAB1

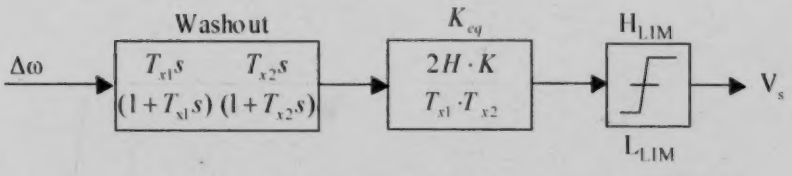


Figure 3.11 Equivalent PSS model of STAB3

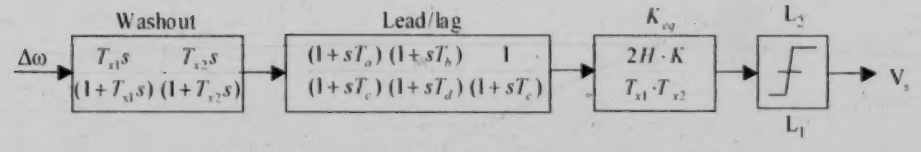


Figure 3.12 Equivalent PSS model of STAB4

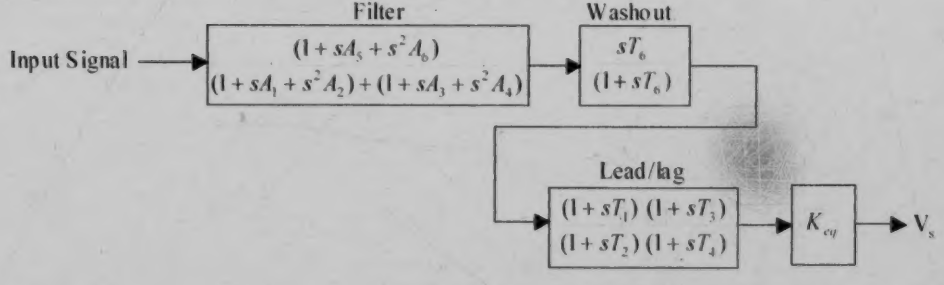


Figure 3.13 Equivalent PSS model of IEEEST

For IEEEST, when input signal is speed deviation or frequency, $K_{eq} = \frac{K_s \cdot T_5}{T_6}$.

When input signal is power, $K_{eq} = \frac{2H \cdot K_s \cdot T_5}{T_6}$ with an additional integrator $\frac{1}{s}$.

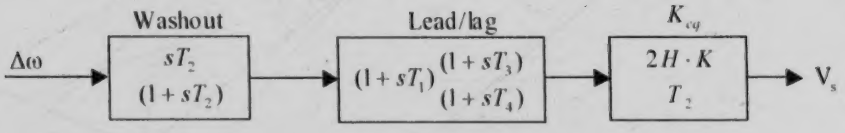


Figure 3.14 Equivalent PSS model of PTIST1

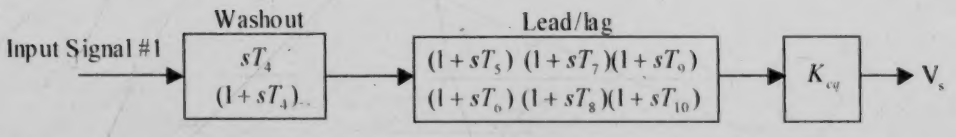


Figure 3.15 Equivalent PSS model of IEE2ST/ST2CUT

For IEE2ST/ST2CUT, when the second input signal is zero, which is true in most applications, and:

- If the first input signal is speed deviation or frequency, $K_{eq} = \frac{K_1 \cdot T_3}{T_4}$.
- If the first input signal is power, $K_{eq} = \frac{2H \cdot K_1 \cdot T_3}{T_4}$ with an additional integrator $\frac{1}{s}$.

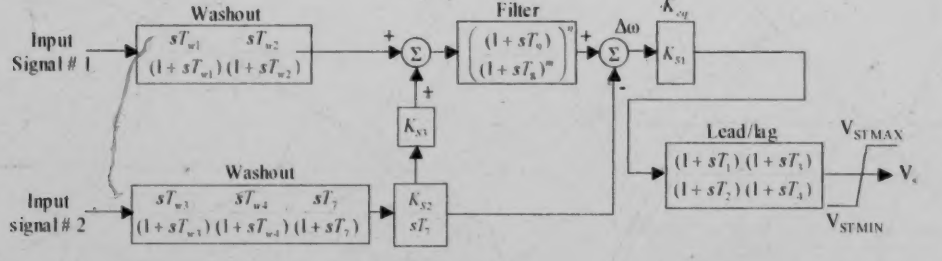


Figure 3.16 Equivalent PSS model of PSS2A

As mentioned in section 3.2.2, only parameters of lead/lag compensator, washout and gain are to be considered because they determine the characteristics of a PSS. All these parameters to be considered can be identified from above diagrams of the equivalent PSS model. Except for the gain, which has been shown in above diagrams, all

the time constants of different types of PSS to be determined are tabulated in the following table.

Table 3.1 Time constants to be determined of different types of PSS

PSS Type	Time constants to be determined	
	Washout	Lead/lag
STAB1	T	T_1, T_2, T_3, T_4
STAB3	Tx_1, Tx_2	Not applicable
STAB4	Tx_1, Tx_2	T_a, T_b, T_c, T_d, T_e
IEEEST	T_6	T_1, T_2, T_3, T_4
PTIST1	T_2	T_1, T_3, T_4
ST2CUT	T_4	$T_5, T_6, T_7, T_8, T_9, T_{10}$
IEE2ST	T_4	$T_5, T_6, T_7, T_8, T_9, T_{10}$
PSS2A	$T_{w1}, T_{w2}, T_{w3}, T_{w4}, T_7$	$T_{s1}, T_{s2}, T_{s3}, T_{s4}$

3.4 PSS Placement

The first step in the PSS design/tuning procedure is to find the location of PSS. Location determination plays an important role in the ability of PSS to stabilize a swing mode. In general, there will be one location, which makes optimum use of the controllability of a PSS. If the PSS is placed at a different location, a larger effort may be needed to achieve a desired stabilization objective. Thus, to add damping to a particular system mode, PSS cannot be arbitrarily placed on the most convenient generator.

In this project, the method of PSS placement depends on PSS design/tuning objective, which is introduced in Section 3.2.1. When PSS is designed/tuned for some

specific generators, the placement of PSS is obviously obtained by specifying the target generators. If the PSS design/tuning objective is a set of specific modes, PSS placement will be determined by the participation factor.

As described in Section 2.1.2.1, participation factor indicates the relative contributions of the respective states to the individual modes. It is a convenient screening tool for obtaining an initial indication of potential sites for PSS. Since participation factors measure the sensitivity of an eigenvalue to changes in the diagonal elements of the state matrix. A speed participation factor indicates the sensitivity of the eigenvalues to changes in the damping torque coefficient of the corresponding generating unit. Therefore, the speed participation factor is a good indicator of the effect that a PSS at the generator will have on the stability of the mode of concern, and can be used to select possible location for the PSS application [9].

If the speed of a generator has a small participation factor in a mode, then that generator is not a good location to control the mode by using PSS. In most cases, the converse situation is also true, i.e., a high and positive speed participation factor of a generator means that a PSS can produce effective damping torque. For the same generator, if the magnitude of its positive participation factor for mode A is much larger than that for mode B, then the damping provided by a PSS at this generator for mode A should be correspondingly larger than that for mode B.

Although in some special cases, a high participation factor does not guarantee the effectiveness of a PSS. For example, a large equivalent generator, which resonates with the inter-area mode, may have spuriously high participation factor [9]. Compared with other methods of PSS location determination, which are tedious and time consuming, the method based on participation factor requires little additional computation, and in most case, is an effective and reliable screening tool for placing PSS.

3.5 PSS Parameter Determination

Based on the general consideration of PSS parameter determination described in Section 2.2.3, this section will discuss the detail approach for PSS parameter determination of this project.

The aim of PSS design/tuning is to provide a torque on the generator rotor that is in phase with the speed variations. To achieve this aim, the procedure of determining PSS parameters consists of two basic steps:

1. Determine the stabilizer time constants to yield a phase compensation specified for required or best performance.

2. Determine the gain based upon gain margin and the required performance.

3.5.1 Time Constants Tuning

As indicated in Section 3.2.2, there are two types of time constant parameters to be determined for the PSS design/tuning. One is for the washout, and the other is for the lead/lag compensator.

3.5.1.1 Time Constants of Washout

Washout block serves as a high pass filter, in which the time constant should be high enough to allow input signals associated with oscillation in rotor speed to pass unchanged. Without it, steady changes in speed would modify the field voltage. It allows PSS to respond only to changes in speed [35]. The typical function of a washout block is shown in Equation 2-33, where T_w is the time constant to be determined.

According to the tuning objective for the washout described in Section 2.2.3, the value of T_w is not critical. But it still has some effect on performance of the designed/tuned PSS. To explain this effect, the magnitude and phase characteristics of a washout with different T_w of 3s and 10s are shown in Figure 3.17 and Figure 3.18 respectively. Figure 3.19 illustrates the corresponding tuned phase characteristics of a STAB1 type of PSS, which is tuned for a poor damped local mode of the specific generator. The function of the lead/lag compensator of this PSS is $\frac{1+0.1s}{1+0.02s}\frac{1+0.11s}{1+0.03s}$.

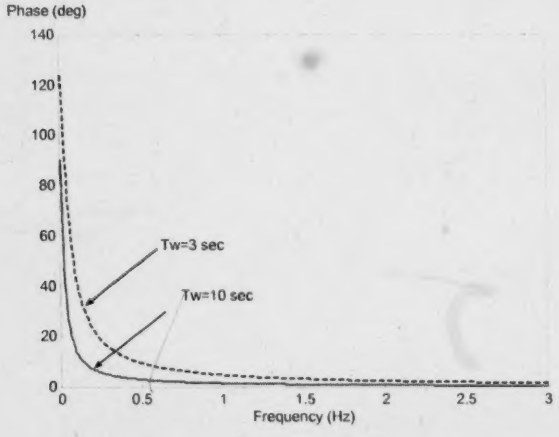


Figure 3.17 Phase characteristics of washout with different T_w

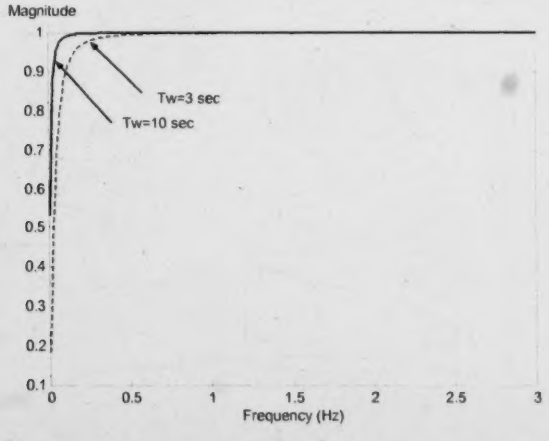


Figure 3.18 Magnitude characteristics of washout with different T_w

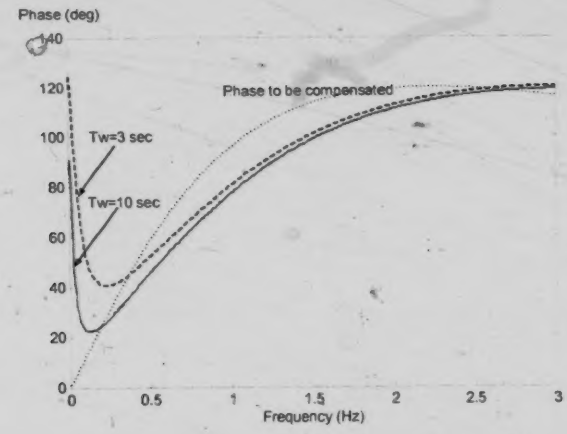


Figure 3.19 Phase compensation of PSS with different T_w

Figure 3.17 and Figure 3.18 show that, as a high-pass filter, washout rejects the low frequency signals while letting the high frequency signals pass. The higher the value of T_w, the better performance the washout can be obtained.

From Figure 3.19, it can be seen that, when frequency is relatively high, the difference between PSS phase compensation with T_w of 3s and 10s is very small. Therefore, the local modes are largely unaffected by changes in T_w. However, a T_w of 3s results in much more phase overcompensation than for $T_w = 10s$ at low frequencies, which is undesirable from the viewpoint of inter-area oscillations. One should be cautious when tuning an inter-area mode with a very small washout time constant. However, T_w should be short enough so that the terminal voltage will not be unduly affected by overall system speed variations, considerate system islanding conditions, where applicable [47].

In this project, for the purpose of industry application, any values of T_w in the range of 1 to 3 second are acceptable with a default value of $T_w = 2s$.

3.5.1.2 Time Constants of the Lead/Lag Compensator

The main concern for determining parameters on the PSS phase compensation is to tune the time constants of the lead/lag compensator, which has a significant impact on the PSS phase characteristics.

The PSS compensator normally has two or three first order lead/lag blocks to achieve the desired phase compensation. For a PSS compensator with n lead/lag blocks, the corresponding function is shown in the form below.

$$\frac{1+sT_1}{1+sT_2}\cdots\frac{1+sT_{2j-1}}{1+sT_{2j}}\cdots\frac{1+sT_{2n-1}}{1+sT_{2n}}$$

where j th lead/lag block is defined as

$$\frac{1+sT_{2j-1}}{1+sT_{2j}}$$

where T_{2j-1}, T_{2j} are the time constants to be determined.

If angle (θ) of the j th block is positive, then the phase compensation provided by the i th block is a lead; otherwise, it is a lag. The maximum angle, θ_m, that the j th block can provide is given by

$$\sin\theta_m = \frac{1-a_j}{1+a_j} \tag{3-1}$$

where $a_i = \frac{T_{2j}}{T_{2j-1}}$. The frequency at which this maximum occurs is

$$\omega_m = \frac{1}{\sqrt{a_j}T_{2j-1}} \tag{3-2}$$

To determine the time constants for the PSS phase compensation, the first step is to get the objective phase to be compensated by obtaining the frequency response of the machine's electrical torque to a small step change in the exciter input. As described in Section 2.3.2.1, the objective phase characteristics are obtained as a function of frequency with a large inertia assumed for the machine under consideration and infinite buses for all the other machines.

The following two parts describe the details of parameter determination for lead/lag compensator.

1. Objective function and optimization technique [30]

In this project, a constrained optimization technique is used to set the compensator time constants. Objective function and constraints that are used in the proposed method are shown below:

$$\text{Minimum } J = \sum_{f_i = f_{\min}}^{f_{\max}} ((\phi_{tuned}(f_i) - \phi_{obj}(f_i))^2 \tag{3-3}$$

with

$$\phi_{tuned}(f_i) = \sum_{j=1}^{n} \phi_j(f_i) = \sum_{j=1}^{n} (\arctan(2\pi f_i T_{2j-1}) - \arctan(2\pi f_i T_{2j})) \tag{3-4}$$

subject to

$$\max(\phi_j(f_i)) \le \varphi_{prac} \tag{3-5}$$

$$\max(\phi_{tuned}(f_i) - \phi_{obj}(f_i)) \le \varphi_{over\_tol} \tag{3-6}$$

$$\min(\phi_{obj}(f_i) - \phi_{tuned}(f_i)) \ge \varphi_{under\_tol} \tag{3-7}$$

$$\max\left|\phi_{tuned}(f_{spec}) - \phi_{obj}(f_{spec})\right| \le \varphi_{spec} \tag{3-8}$$

$$T_{\min} \le T_{2j-1} \le T_{\max} \tag{3-9}$$

$$T_{\min} \le T_{2j} \le T_{\max} \tag{3-10}$$

where

ϕ_{obj} is the PSS objective phase obtained from frequency response (degree),

ϕ_{tuned} is the PSS phase to be determined (degree),

ϕ_j is the phase of j th lead/lag block to be tuned (degree),

f_i is each frequency point considered (Hz),

f_{spec} is the specific frequency (Hz),

$f_{\min}$ is the minimum frequency of interest (Hz),

$f_{\max}$ is the maximum frequency of interest (Hz),

i is the number of simulation points from frequency $f_{\min}$ to $f_{\max}$,

j is the number of lead/lag blocks of the PSS compensator,

T_{2j-1} and T_{2j} are the time constants of j th lead/lag block (second),

$T_{\min}$ is the minimum limit of time constant (second),

$T_{\max}$ is the maximum limit of time constant (second),

φ_{prac} is the maximum phase limit for each lead/lag block (degree),

φ_{over_tol} is the maximum phase overcompensation limit (degree),

φ_{under_tol} is the minimum phase under-compensation limit (degree),

φ_{spec} is the tolerance of compensation error for a specific frequency f_{spec} (degree).

The objective function of the above optimization problem as defined by Equation 3-3, is to fit the objective phase and the PSS phase to be designed/tuned. All the non-linear constraints are defined by the equations from Equation 3-5 to Equation 3-10.

Equation 3-5 specifies the maximum phase compensation that can be provided by each lead/lag block under practical consideration, normally φ_{prac} is 60 degree. Thus, for practical combinations of lead/lag networks, phase compensation can only be provided up to about 120 degree with two lead/lag functions. In many applications, the total amount

of phase compensation that can be usefully employed is limited by the considerations of the noise vulnerability [46]. The constraints of over or under-phase compensation can be specified by Equation 3-6 or Equation 3-7. Equation 3-8 gives the constraint for phase compensation at a specific frequency point. The limits of time constants to be determined are set by Equation 3-9 and Equation 3-10.

Constraints specified by Equation 3-6, 3-7 and 3-8 are illustrated by the following figures. As shown in Figure 3.20 and Figure 3.21, over or under compensation constraint can be specified by setting a tolerance within frequency range of interest. As described in Section 2.2.3, under-compensation is normally preferred rather than overcompensation. In Figure 3.22, the compensation only focuses on a special mode with a certain frequency f_{spec}. The constraint is specified by a compensation tolerance φ_{spec}.

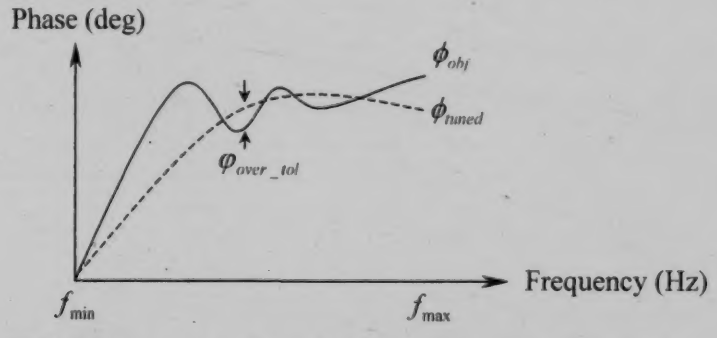


Figure 3.20 PSS phase compensation with overcompensation constrain

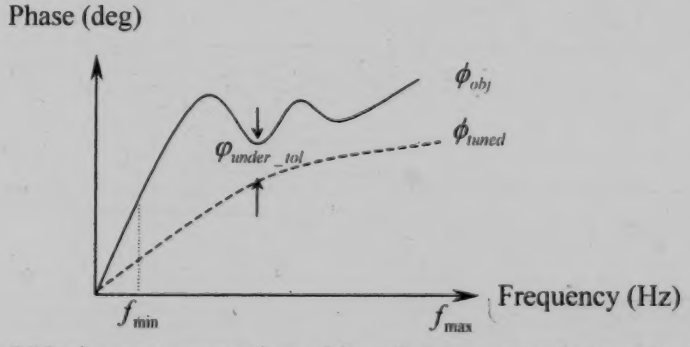


Figure 3.21 PSS phase compensation with under-compensation constrain

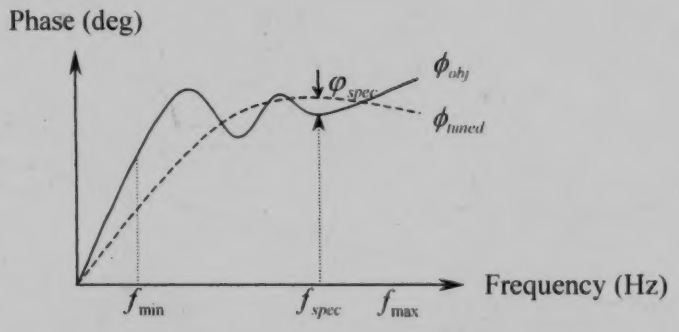


Figure 3.22 PSS phase compensation with specific frequency constraint

Generally, all the constraints to be specified may be one of the following options or their combinations:

1. Different frequency range to be considered.
2. Maximum phase compensation of each lead-lag block.
3. Over or under compensation constraints with a compensation tolerance.
4. Phase compensation for some special frequency.
5. Limits of time constants.

The above constraint #1, #2 and #5 have some default specifications, if constraint #3 and #4 are not specified, an overall optimal compensation will be obtained according to these default specifications. If the specified constraints are in conflict, at first, we disregard the constraint #4. If this is not sufficient, we disregard the constraint #3. This procedure always guarantees the existing of an optimal result. The following figures show different optimal results with different selection of above constraints.

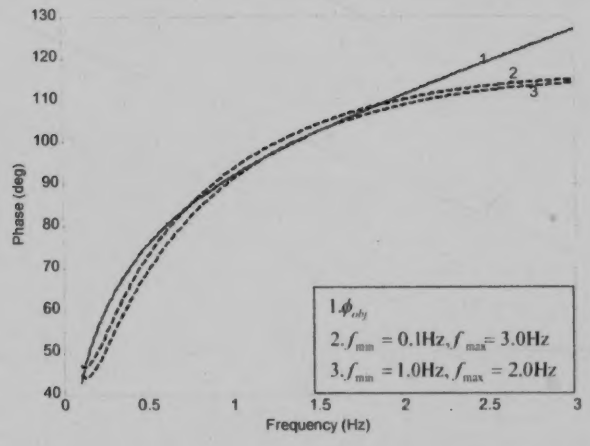


Figure 3.23 Overall PSS tuning in different frequency range

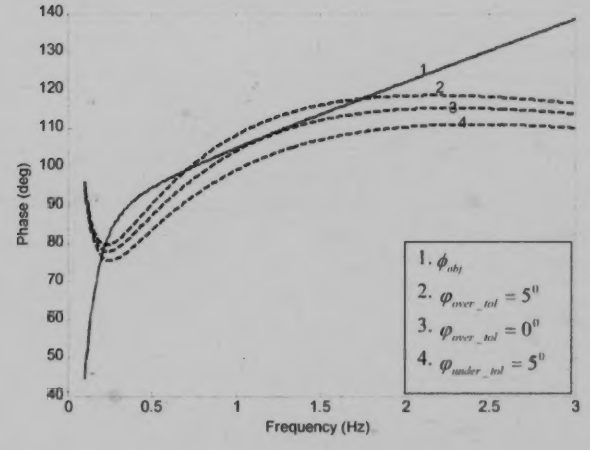


Figure 3.24 PSS tuning in the frequency range of 0.5 Hz to 2.0 Hz with over/under compensation constraint

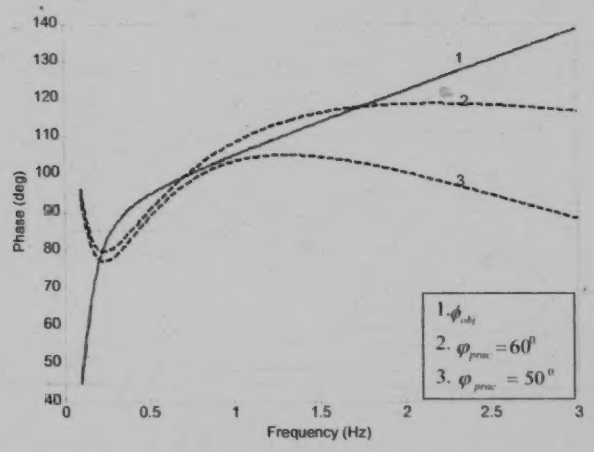


Figure 3.25 PSS tuning with different maximum phase limit for each lead/lag block

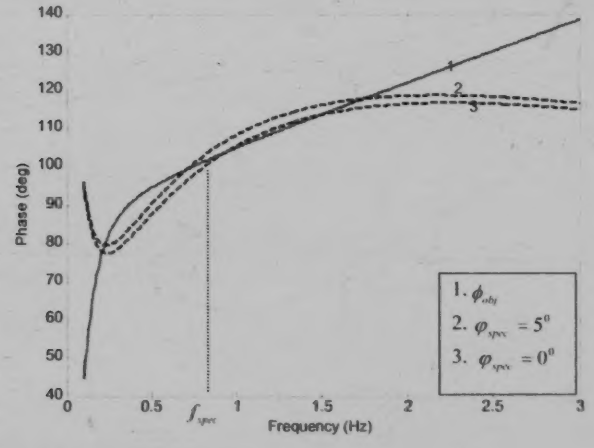


Figure 3.26 PSS tuning for a specified frequency $f_{spec} = 0.8315Hz$

2. Phase compensation criteria

The objective phase obtained from the frequency response includes all the modes concerned in the frequency range of interest. However, for the design/tuning of a conventional PSS, it is impossible to get an ideal compensation for all the modes. So the idea is to choose a dominant oscillation mode or the specified mode to design/tune the PSS, at the same time compatible with the other modes simultaneously to obtain an

overall performance. Some general rules for PSS phase compensation tuning can be obtained by analyzing Figure 3.27, which shows the generator electrical torque with PSS phase compensation at a certain frequency.

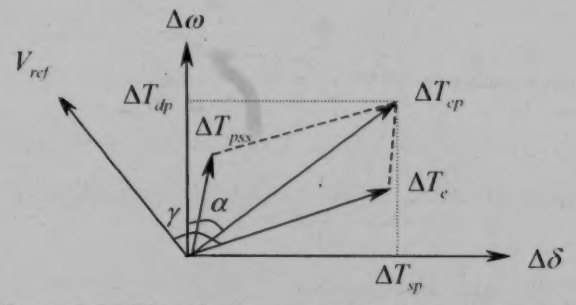


Figure 3.27 Electrical torque with PSS compensation

In Figure 3.27, γ is the phase lag to be compensated from the electrical torque ΔT_e to voltage reference V_{ref}. Before PSS design/tuning, ΔT_e has a small amount of damping component in the direction of speed deviation $\Delta\omega$. With the additional torque ΔT_{pss} provided by the designed/tuned PSS, a new electrical torque ΔT_{ep} is obtained. The angle α is the net phase lag between ΔT_{ep} and $\Delta\omega$ after PSS design/tuning. The damping torque component ΔT_{dp} and synchronizing torque component ΔT_{sp} of ΔT_{ep} are determined by the follow equations:

$$\Delta T_{dp} = \Delta T_{ep} \cdot \cos\alpha \tag{3-11}$$

$$\Delta T_{sp} = \Delta T_{ep} \cdot \sin\alpha \tag{3-12}$$

Note that the perfect phase compensation of PSS implies a zero value of phase lag of α, which is impossible in practice. However, a reasonably effective damping may still occur as long as α less than 45 degree. Since once α is larger than 45 degree, the effectiveness of PSS drops quickly because ΔT_{dp} is directly proportional to $\cos\alpha$. Once α is larger than 90 deg, PSS brings some negative damping into the electrical torque because ΔT_{dp} becomes negative. For a negative value of α, which results in a phase lead

between ΔT_e and $\Delta\omega$, according to Equation 3-12, the corresponding ΔT_{sp} is negative, which gives rise to a desynchronizing influence and will have an adverse effect on the transient stability. Therefore, it is preferable that α is within 0 degree and 45 degree [43].

Generally, the net phase lag (α) of the plant and stabilizer after PSS compensation should be

1. Less than 90 degree for as broad a frequency range as possible. Above 90 degree, the damping effect will become negative. The angle α should be large than 0 degree to avoid the desynchronizing effect [25].

2. Between 0 degree and 45 degree to cover the frequencies range between the lowest inter-area mode frequency to the highest local mode frequency. Because damping contributions are proportional to the cosine of α, for phase discrepancies of up to about 45 degree, the detrimental effects are small.

3. For a high frequency mode, which is outside of the local mode frequency range, overcompensation is not very important. To avoid significant overcompensation, α should be larger than -5 degree.

From the view point of eigenvalue in s-plane, PSS phase compensation should provide only enough phase lead so that the eigenvalue of the considering mode moves perpendicular to the imaginary axis or slightly upward away from the real axis. This will insure that the available synchronizing torque as high as possible with providing good damping of the oscillation mode while still remain stability of the higher frequency mode. Eigenvalue motion downward toward the real axis indicates that the PSS is providing too much phase lead which gives rise to the desynchronizing effect. This will result in the excitation mode becoming unstable at a relatively low synchronizing torque setting [13].

The above criteria make sure that the designed/tuned PSS provide a dominant damping component of torque, which effectively improves the damping of the oscillation mode considered. At the same time, they also produce a positive component of synchronizing torque, which reduces the tendency towards an adverse influence on large transient performance.

3.5.2 Gain tuning

3.5.2.1 Introduction

After time constants of PSS are determined to meet the desired phase characteristics, the gain of PSS is selected to obtain the desired level of damping. Compared with the time constants, which are tuned as optimization results, tuning of the gain is more of a compromise.

Since the gain of PSS has an important effect on the oscillation damping, it should be chosen by examining the effect for a wide range of values. If the gain is very small, damping of the oscillation mode will be too small without satisfying the damping requirement. Ideally, the gain should be set at a value corresponding to the maximum damping [35]. However, the gain determination is often limited by other considerations, for example, too high gain may give rise to unacceptable limit saturation for signals or signal noise.

In this project, the value of PSS gain is set at a balance point in a band consist of a minimum value and a maximum value. The minimum gain is determined by making the PSS design/tuning objective satisfy the performance requirement (a specified minimum damping). Theoretically, the maximum gain is set based on searching gain margin that results in the first unstable oscillation mode, which is normally a control mode. But, it should be noted that the determination of a usable maximum gain is also limited by other considerations such as the noise problem. To avoid a too high gain, it is necessary to set a limit of the maximum gain based on experience. Obviously, the minimum gain makes

more sense by comparing with the maximum gain, which is only given as a guideline value.

Generally, the determination of gain is not as critical as that of time constants. In some cases, it can be set on the basis of engineering experience, or some default value can be chosen between the tuned minimum gain and maximum gain.

In this project, to simplify the treatment, the gain tuning is done analytically with root-locus of mode trace. The idea of root-locus of mode trace is to trace a number of modes by root-locus plot for a given sets of parameters. Figure 3.28 shows an example in which one mode is traced following the gain (K_i) change of a PSS.

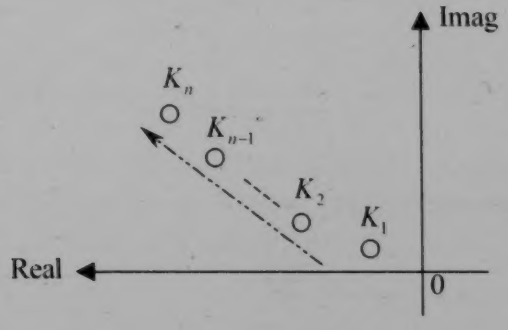


Figure 3.28 An example of a mode trace following the PSS gain change

If more than one PSS gain has to be determined during each mode trace procedure, the adjustment method of root locus points are "aligned", which means all gains proceed to next value in their range together, until all gains have reached their last points.

The following two sections explain how to determine these gain values.

3.5.2.2 Determination of Minimum Gain

Generally, the minimum gain is tuned in order to make the PSS design/tuning objective satisfy the performance criteria. The tuning procedure is different according to different PSS design/tuning objective, which is described in Section 3.2.1.

1. Tune for specified modes

In total there are three methods available to determine the minimum gain when tuning the specific modes.

- Method 1

After the time constants are determined, find the poorest damped mode among all the target modes, then trace this mode by modifying the gain of all designed/tuned PSS aligned with a certain step, until the gain value is found, which makes this mode satisfy the performance requirement. This gain is set as the minimum gain of all designed/tuned PSS. This method is simple and easy to be implemented. However, sometimes, it gives rise to unreliable results because the least damped mode may change with the variation of PSS parameters.

As shown in Figure 3.29, mode 1 and mode 2 are the objective modes to be considered. Compared with mode 2, mode 1 is more poorly damped at the beginning of the mode trace with a damping less than ζ_0. With the change of the stabilizer gain, mode 2 becomes more poorly damped than mode1 before mode 2 satisfies the performance requirement ζ_{req}. The reason is that the increment of damping for different modes is different when PSS gains change. Now, if the gain is still determined according to tracing mode 1, a misleading result will be result in. Therefore, it is not reliable to tune the minimum gain based only on tracing the least damped mode.

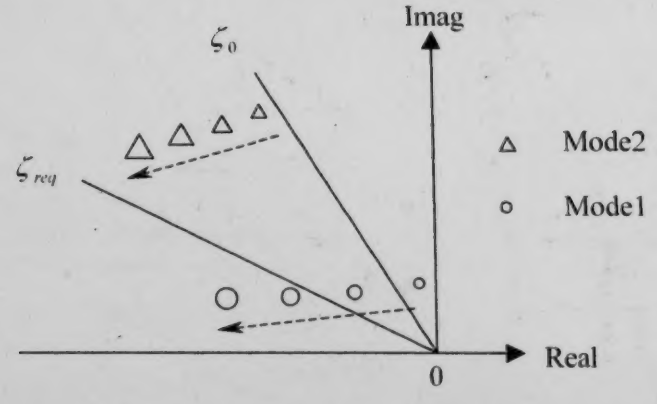


Figure 3.29 Root-locus plot with the gain change of PSS

- Method 2

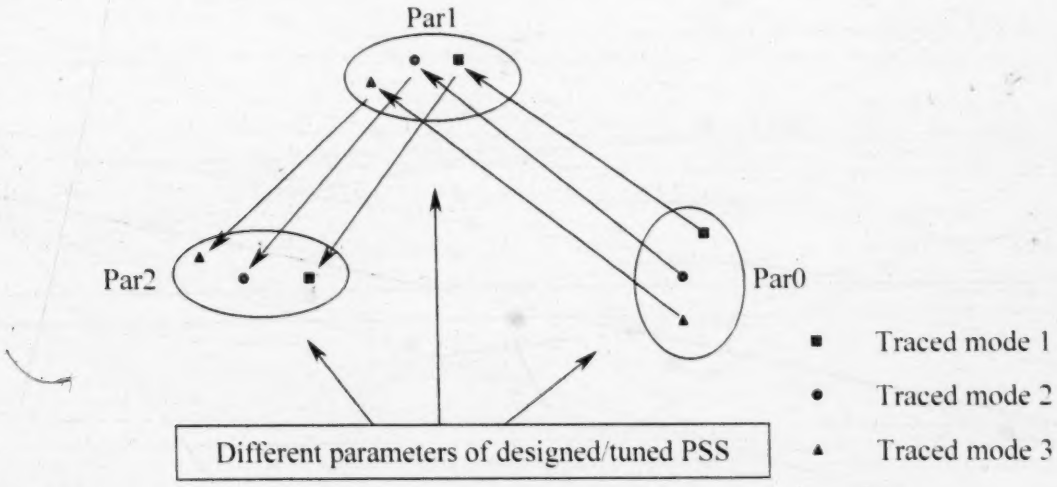
Starting from a very small value of all PSS gains to be considered, calculate all the new objective modes as all the gains vary with a certain step. Then, the minimum gain is set as the value for which all the objective modes satisfy the performance requirement. For this method, the drawback is that some objective modes may be missed during this tracing procedure, e.g., they may be out of the frequency range of interest as gains varies. Another possibility is that some objective modes may become uncontrollable by the target PSS. Furthermore, with the change of gain, some new poorly damped modes may be involved within the concerned frequency range. Therefore, this method is also unreliable.

- Method 3

Compared with above two methods, the reliable way is to check and trace all the objective modes one by one with PSS gain changing. First of all, check all the objective modes and obtain all target modes by removing those modes, which are either not controllable by the considered PSS or satisfy the requirement already. By individually trace each target mode, the corresponding minimum gain is determined to make this target mode satisfy the performance requirement. Then, to ensure that all the target modes satisfy the performance requirement, the highest of the minimum gains is set as

the minimum gain for all the designed/tuned PSS. Compared with methods above, this method guarantees the reliability of the minimum gain determination, and therefore it is adopted in this project.

The determining of the time constants and gain are two separate procedures, and during each procedure, the target mode is changeable according to the variation of these parameters. After the tuning of time constants and before the gain tuning, the original target modes have changed with the new time constants. So the gain tuning should be carried out based on these new target modes but not the original ones. To find these new target modes, the original modes should be traced with the variation of time constants. Then, the minimum gain is determined by tracing these new target modes for gain change. Therefore, one needs two processes of mode trace to determine the minimum gain, which is shown in the following figure.



where

Par0 are the original parameters before PSS design/tuning.

Par1 are the parameters with the tuned time constants and the original gain.

Par2 are the parameters with the tuned time constants and the tuned gain.

Figure 3.30 Mode trace procedure for determination of the minimum gain

In Figure 3.30, there are three target modes to be considered. Two tracing procedures are done about these three modes to determine the minimum gain of PSS. The first step is to trace all the target modes from the original parameters "Par0" to the parameters "Par1" where all the PSS time constants are tuned but all original gains remain constant. Then all new target modes are obtained with parameters "Par1". Based on these new target modes, the minimum gain is determined by the mode tracing from the parameters "Par1" to parameters "Par2". In this procedure, only the gains change while retaining all the tuned time constants, until all the new target modes satisfy the performance requirement. Thus, the obtained gain is set as the minimum gain.

Figure 3.31 and Figure 3.32 illustrate the above procedures when PSS are designed/tuned for an inter-area mode with a performance requirement of 5% damping. The corresponding eigenvalue results are given in Table 3.2 where K_{min} is the determined minimum gain.

Table 3.2 shows that the damping of the original mode is 3.15% before PSS design/tuning. It changes into 2.67% after the tuning of time constants. The corresponding mode trace is shown in Figure 3.31. One can see that the considered mode is more poorly damped with the new time constants of PSS. The reason is that the phase of the original PSS has significant overcompensation while it is mitigated by the new time constants, thus the corresponding damping has decreased.

In Figure 3.32, the starting point for gain tuning is now the mode with a damping of 2.67%. This mode is traced with PSS gain change. It can be seen that damping increases while gain of PSS goes up in this mode trace process. After checking the eigenvalue of traced point with a different value of PSS gain, a minimum gain $K_{min} = 9.0$ is found, which makes the target mode satisfy the 5% damping requirement. Actually, the minimum gain is determined as a threshold according to the performance requirement, that is, the traced mode does not satisfy the performance requirement when

the gain is less than this value, and all the gains above this value make the traced mode satisfy the performance requirement.

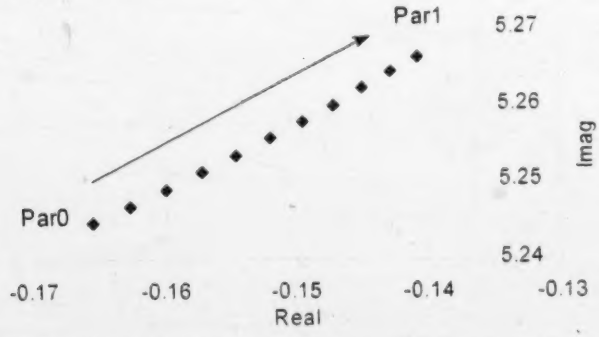


Figure 3.31 Mode trace for time constants tuning

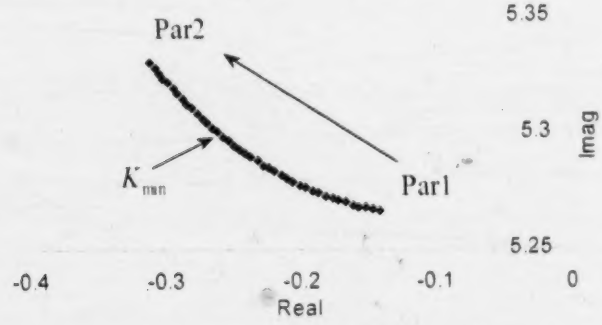


Figure 3.32 Mode trace for minimum gain tuning

Table 3.2 Eigenvalues of the considered mode with different PSS parameters

PSS Parameters	Eigenvalue	Frequency (Hz)	Damping (%)
Par0	-0.1655+j5.2448	0.8347	3.15
Par1	-0.1406+j5.2663	0.8382	2.67
Par2	-03088+j5.3308	0.8484	5.78
$K_{min} = 9.0$	-0.267+j5.3044	0.8442	5.00

In most cases of the objective for specific modes, one has to design/tune multiple PSS. The following figures illustrate the minimum gain determination of multiple PSS. In Figure 3.33 and Figure 3.34, there are two objective modes, mode m and mode n to be

concerned. According to their participation factors, PSS_i and PSS_j have large controllability of these two modes. ζ_{init_m} represents the initial damping of new mode m with parameters "Par1" after the time constants are tuned. Since ζ_{init_m} is less than the damping requirement ζ_{req}, the gain of PSS_i and PSS_j should be increased to improve the damping of mode m. The mode n has the inverse situation, which is shown in Figure 3.34. K_{init} is the initial gain value of these two PSS.

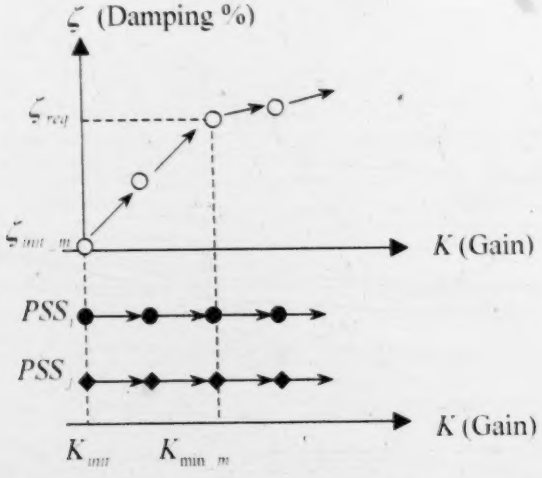


Figure 3.33 Tracing of mode m to search the minimum gain

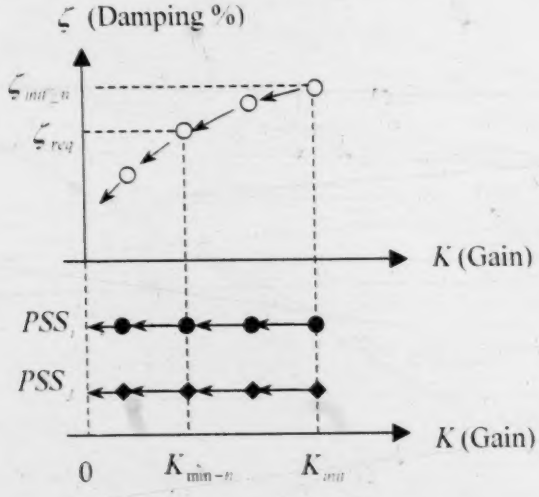


Figure 3.34 Tracing of mode n to search the minimum gain

By tracing mode m and mode n separately when gain of PSS_i and PSS_j change simultaneously, $K_{\min-m}$ and $K_{\min-n}$ are found as the minimum gains to make damping of mode m and mode n satisfy ζ_{req} respectively. To make both of modes satisfy the performance requirement, $K_{\min-m}$, which is larger than $K_{\min-n}$ is set as the searched minimum gain for PSS_i and PSS_j.

After the minimum gain is determined based on mode trace, a verification is also needed to make sure that not only the specified inter-area modes, but also all the local modes related to generators considered satisfy the performance requirement, otherwise, the minimum gain should be increased until all the local modes are satisfied.

2. Tune for specified generators

If PSS are designed/tuned for specific machines, the minimum gain is searched independently for each machine. Each minimum gain is determined to make all the poorly damped local modes of target machine satisfy the performance requirements. All the local modes of target machine are checked step by step as its PSS gain changes until the minimum gain is found.

It should be noticed that during this process, with the change of stabilizer gain, the speed participation factors of the target generator maybe become too small to make the considered poorly damped modes controllable enough. In this case, these modes should be dropped from the objectives because they may not satisfy the performance requirement even with a very large gain value of the designed/tuned stabilizer. So, local modes and the corresponding participation factors must be checked as stabilizer gain varies in each step.

The reason for not using the mode trace to determine the minimum gain for this objective is the following:

1) Local mode is very sensitive to the variation of parameters. The results of local mode trace could be unreliable.

2) Second, as described above, the participation factors are also changed as the corresponding mode changes, and thus it is hard to identify those uncontrollable modes related to the target generator during the process of mode trace. A misleading result maybe occurs without eliminating the uncontrollable modes by the considered PSS.

3.5.2.3 Determination of Maximum Gain

As mentioned in Section 3.5.2.1, the maximum gain is determined by searching the gain margin of the concerned PSS. For both PSS design/tuning objectives, the procedure of searching the maximum gain is done for one PSS at a time.

The idea is to gradually increase the gain of target PSS until an unstable mode occurs. This obtained gain is the gain margin. For a good stability of the control loop of PSS, the maximum gain should be reduced to about one-third of the gain margin [45]. However, in some cases, the optimal gain does not coincide with the maximum gain determined by the gain margin. Thus, further correction may be necessary using the gain of one-third of the gain margin as the starting point. This approach can be explained by Figure 3.25 where a specified mode is traced as PSS gain increases.

In Figure 3.35, gain at point C is the gain margin for the target PSS for which the first unstable occurs. Gain at point B is the ideal maximum gain, which is about one-third of gain at point C. The gain at point A is determined as the final maximum gain for the tuned PSS. The reason is that further increasing in gain results in a decreasing in damping

once the considered mode is beyond point A. Compared with the eigenvalues at other points, the eigenvalue in point A has the fastest decay time constant determined by the largest magnitude of a negative real component. Since the oscillation mode in point A is crisp and sensitive to gain change, to get a high damping, the gain in point A should be set as the usable maximum gain even though it is smaller than that at the point B.

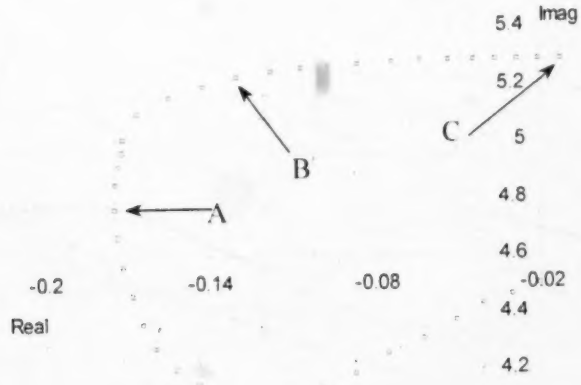


Figure 3.35 Mode trace as PSS gain increases

With above consideration of obtaining a high damping, the maximum gain should also be determined without adverse effect on the stability of other system modes. The following plot is to investigate this issue.

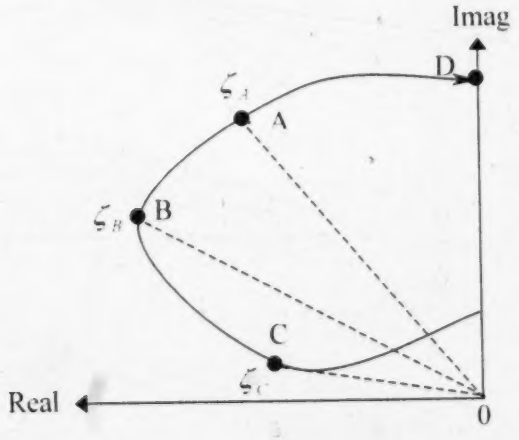


Figure 3.36 Mode location with different PSS gain

In Figure 3.36, the eigenvalue of a certain mode changes with the variation of the PSS gain. There are three mode locations A, B and C with different gain to be compared. The respective damping is ζ_A, ζ_B and ζ_C. The corresponding generator electrical torque change is ΔT_{eA}, ΔT_{eB} and ΔT_{eC}, which are shown in Figure 3.37. Each electrical torque change is split into damping torque component and synchronizing torque component according to the definition in Equation 1-1.

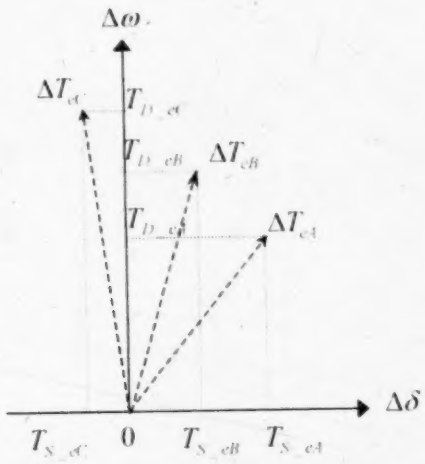


Figure 3.37 Generator electrical torque with different PSS gain

From Figure 3.36, according to the definition of damping ration in Equation 2-22, it is easily found that mode at point C has the largest damping while mode at point A has the poorest damping. Mode at point B is crisp with the fastest decay time constant as explained by Figure 3.35. If only consider the criteria that the maximum gain should be set at a value corresponding to a maximum damping, the gain value at point C will be chosen as the maximum gain. However, it is not true when considering the issue that PSS should improve the overall stability of the system. The corresponding explanation is as follow.

According to the relationship between frequency and synchronizing torque, which is derived from Equation 15 of Appendix A, it is known that when frequency is lower, the corresponding synchronizing torque, which is in the direction of the angle deviation decreases too, and the decreased synchronizing torque may give rise to transient instability. Thus, in Figure 3.37, the mode at point A has the largest synchronizing torque T_{S_cA} while the mode in point C has a negative synchronizing torque component T_{S_cC}. So, PSS with gain at point C gives rise to some adverse effect on synchronizing torque even it adds a positive damping component T_{D_cC}. Although mode in point A brings the largest synchronizing torque T_{S_cA}, the corresponding damping T_{D_cA} is not large enough. Therefore, point B is the best operation point as both a relatively large damping torque T_{D_cB} and a positive synchronizing torque T_{S_cB} are provided. Therefore, the usable maximum gain, which is determined by point B, is not necessarily the maximum gain value determined by gain margin, which is at point A, neither the gain with the maximum damping, which is at point C.

After the maximum gain is found, one should check the maximum gain limit to avoid the situation where no unstable mode occurs even the gain is already very large. In this case, the maximum gain is set at the limit value to avoid the problems of noise and saturation of the stabilizer.

From above analysis, it can be found that the safely usable maximum gain depends upon many factors, and in practical application, it is best determined or verified by field-testing. On-line field-testing is necessary to ensure that the parameters used for off-line analysis are accurate. The field-testing can be conveniently done by inserting a small step signal in place of the speed or frequency deviation signal and measuring the response of terminal voltage. A detailed information about field-testing can be found in Reference 39,42 and 44.

Theoretically, the use of a plot relating damping and synchronizing coefficients will give a good explanation for gain determination. Unfortunately, these coefficients are well defined only for a simple system representation, such as a single machine connected to an infinite bus (See Appendix A), and for a simple machine representation [41]. Therefore, for off-line analysis, technique based on gain margin and some post computation is used to determine the theoretical maximum gain of the designed/tuned PSS. On-line field-testing is necessary to verify the maximum gain before the industrial application.

3.5.2.4 Results of Gain Performance Matrix

After the gain tuning, each designed/tuned PSS has a gain band limited by the minimum gain and the maximum gain. To get more information about the PSS behavior with different gain value, each gain band is uniformly divided into several groups. Then an eigenvalue matrix of the PSS design/tuning objective can be calculated for each group of gain. A gain performance matrix about some modes is depicted in Figure 3.38.

In Figure 3.38, a total of m PSS are designed/tuned for the considered mode. $K_{\min(i)}$ and $K_{\max(i)}$ are the respective minimum gain and maximum gain for PSS_i, and they constitute a gain band for the i th PSS. All the gain bands of m PSS are divided into n groups uniformly. For each group of gain from $K_{j(1)}$ to $K_{j(m)}$, an eigenvalue λ_j of the considered mode is obtained. Thus with the sufficient information provided by these n groups of eigenvalues, the proper gain can be easily determined for the desired performance.

If the PSS are designed/tuned for specified generators, the corresponding gain performance matrix is calculated one by one for each objective local mode.

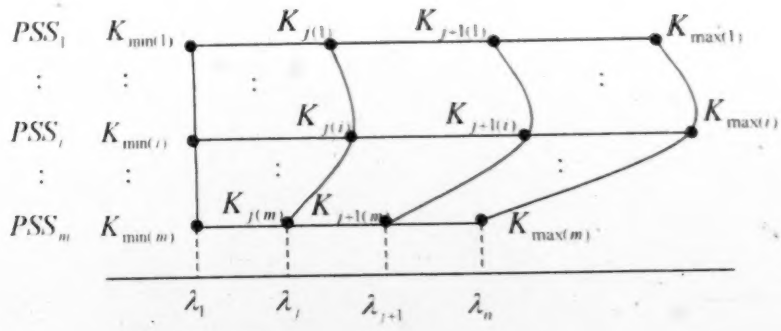


Figure 3.38 Gain performance matrix of a certain mode

Since the method and criteria for searching the minimum gain and maximum gain are different, there are some situations, which may easily give rise to an unreasonable result, e.g., the minimum gain becoming larger than the corresponding maximum gain. This can be caused, e.g., by specifying a too high performance requirement. Another possibility is due to the difference of tuning step. If tuning step of the minimum gain is very large while that of the maximum gain is very small, at the end the obtained minimum gain could be larger than the maximum gain. Therefore, reasonable and practical performance requirements, tuning step and gain limit should be provided during the gain determination procedure.

3.5.3 Discussion

After the description and analysis of the proposed PSS design/tuning approach proposed, it is apparent that the advantages of this approach are:

1. It is simple to get the phase characteristics of the target PSS because it only requires the dynamic characteristics of the concerned machines to be modeled in detail. The proposed parameter determination methods are optimal and flexible.

2. It is straightforward to obtain the system performance by calculation the specified performance criteria.

3. It is practical and suitable for large systems without any limitation coming from the scale of the system.

4. The designed/tuned PSS can improve the overall system behavior, not only for one specified mode or machine.

The limitations are,

1. To improve the overall system performance, phase compensation must be balanced between different modes. It is hard to get a perfect design.

2. No direct information can be obtained about the added damping torque and synchronizing torque.

Since the above limitations come from the limitations of PSS structure, modeling of power system etc., they are not major concerns for the implementation of this method.

3.6 PSS Design/Tuning Logic

Appendix B shows the flow chart for the proposed PSS design/tuning logic. With this toolbox, user can not only study the state of power system, e.g., the oscillation problem, but also obtain the control scheme, which includes:

- The location of PSS
- PSS design or tuning

If some PSS are already installed, tuning these PSS will help to verify the current PSS parameters and analyze the effect on system. On the other side, the

best parameters can be retuned with respect to some specified requirement of local or inter-area modes.

If there are none PSS installed, then location of new PSS is determined, and parameters are designed based on some recommended type. In the practical application, the new PSS is only considered if it is found that the modification of existing PSS is either not feasible or not sufficient. The reason is that the installed PSS in some old machines may be ineffective, and installation of PSS in all new machines is expensive and not necessary.

- Performance index calculation for PSS verification

The proposed determination methods of PSS parameters are to provide an overall stability. To verify this approach, some specified performance indices are calculated to prove that the designed/tuned PSS improve the small-signal performance as well as the large-signal performance.

Several issues to be considered in the proposed design/tuning logic are described as follows:

1. Candidate machine list

The candidate machine list provides the information of all units where PSS need to be designed/tuned. Table 3.3 and Table 3.4 give some examples with different PSS design/tuning objectives.

When PSS is designed/tuned for specified modes, all the candidate machines are selected based on post-analysis of the participation factors. Firstly, modes related to the PSS design/tuning objective are identified by modal analysis. Then, for each mode to be concerned, its candidate generators are determined according to the corresponding

participation factor. To make the PSS design/tuning effective, the mode to be concerned should be controllable enough by its candidate generators, i.e., the corresponding participation factor of the candidate generator should be larger than a small threshold, which is set to 0.2 in this project. If there are more than one specified modes to be considered, sort all the candidate generators in the descending order according to their participation factors in each mode. Then a general candidate machine list, which includes all the candidate machines relating to all the specified modes, is obtained. If one candidate generator has several participation factors to control more than one mode, only the largest participation factor is considered when determining this generator's position in the candidate list. This is to avoid the conflicting situation where the same PSS is required to be designed/tuned several times for different modes. Thus, PSS will be designed/tuned according to this general candidate machine list.

Table 3.3 Candidate machine list of PSS design/tuning for specified modes

Candidate generator					Specified modes	
BUS Number	BUS ID	PSS Type	Exciter Type	Participation Factor	Frequency (Hz)	Damping (%)
101	1	PTIST1	IEEET1	1.0	0.835	3.15
102	2	IEEEST	EXAC1	0.91	0.810	2.78
...	...	...	...	...	...	...

Table 3.4 Candidate machine list of PSS design/tuning for specified generators

Specified or Candidate Generators				
BUS Number	BUS ID	PSS Type	Exciter Type	Area Number
101	1	PTIST1	IEEET1	1
102	2	IEEEST	EXAC1	2
...	...	...	...	...

In Table 3.4, when PSS are designed/tuned for specified generators, the candidate generators are the same as the specified ones, which may be identified by geographical areas. PSS design/tuning are carried out based on computation of modes related to each generator individually.

For both objectives, user can edit the candidate machine list by manually adding or removing some generators.

2. Mode-list:

The objective of determining mode-list is to coordinate all modes, which are related to the candidate generator, to avoid any adverse effect on the other modes when design/tuning PSS for one specific mode.

For example, when design/tuning for some inter-area modes, the PSS to de signed/tuned should also ensure good performance for the associated local modes. Similarly, when the objectives are local modes, damping enhancements should also be made to the inter-area modes, which are controlled by the corresponding candidate generators. Thus, besides the target modes of the PSS design/tuning objective, it is also necessary to identify additional modes required during PSS parameter determination. These refer to:

- Local models of the machines whose PSS are to be designed/tuned for specified inter-area modes

- Inter-area modes associated with the machines whose PSS are to be designed/tuned for local modes

- Control modes of the machines should also be monitored to ensure that they are not adversely affected by the PSS design/tuning

A mode-list consists of the above modes for each candidate generator. During the PSS parameter determination, an overall optimal result can be achieved by coordinating all modes in the mode-list.

3. Verification of the design and evaluation of the performance

As described in Section 2.2.4, the system performance should be verified after PSS are designed/tuned. To determine if the system with the designed /tuned PSS satisfies the performance requirements and design constraints, there are two kinds of verification to be done in this project.

The first one is the small-signal performance verification in frequency-domain, which is implemented by modal analysis. Here, the new eigenvalue matrix of the objective oscillation modes with the designed/tuned PSS is checked by the performance requirement. The second verification concerns the large-signal performance verification in time domain. To test the robustness of the designed/tuned PSS, time domain simulation should be applied over a wide range of operating conditions and system disturbances. In this project, it includes a standard generator step response and simulation with some specified contingencies under disturbance.

4. Difference between PSS tuning and PSS design

PSS design is only meaningful for those candidate machines, which are already equipped with excitation system. The process of PSS design is similar to that of the tuning problem. The unique aspect is the PSS type is to be determined.

In this project, a conventional PSS type, e.g., $\Delta P/\omega$ is recommended. As one of the most widely used $\Delta P/\omega$ PSS in the system of North America, PSS2A is the recommended type to install the new PSS. The corresponding block diagram is shown in

Figure 3.8. As described in Section 2.2.2. this type of PSS has many advantages and removes many limitations inherent in the use of other type of PSS. thus this type of PSS will be considered for new PSS design.

3.7 PSS Design/Tuning Tools - Program Package Introduction

Except for the internal design/tuning of PSS as a controller. a combination of power system analysis tools is required to successfully determine whether power system oscillations are stable and understand in detail the nature of a particular oscillation mode. The two essential analysis tools that are required are a small signal stability program and a transient stability program.

In this project. the overall environment of this PSS design/tuning toolbox takes the form of a MATLAB optimization toolbox interacting with two essential program packages: small signal analysis tool (SSAT) and transient security assessment tool (TSAT). both of which have been developed by Powertech Labs Inc.. The relationship between these analysis tools is shown in Figure 3.39.

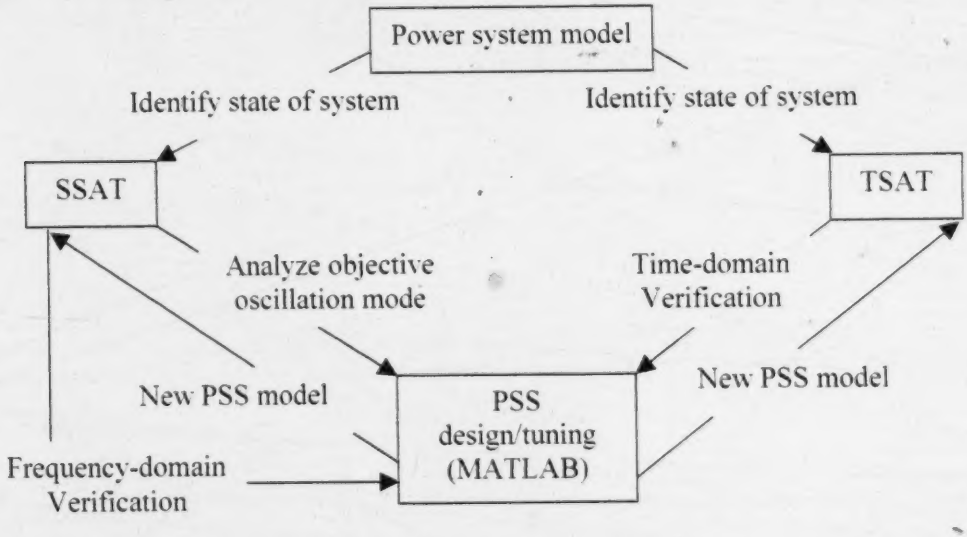


Figure 3.39 Interface of program package for PSS design/tuning toolbox

3.7.1 Small Signal Analysis Tool – SSAT [37]

To improve the oscillation damping by PSS design tuning, the fundamental tool used in this project is the small signal analysis tool-SSAT. SSAT is a state-of-the-art tool in the development of eigenvalue computation techniques and the related numerical analysis. It offers powerful features for small signal stability analysis of power system with comprehensive analysis functions. The main capabilities of SSAT are

1. Conventional eigenvalue analysis for identification of poorly damped modes and design of control system to improve damping.
2. Security assessment capabilities to determine planning and operating guidelines for system with existing or potential damping problems.
3. Validation and tuning of generator and control modes.
4. Potential on-line security assessment.

Its main features include

- Comprehensive and flexible modeling
- Variety of eigenvalue calculation options to address various problems
- Small signal stability index computation
- Frequency/step response computation
- Contingency analysis
- Sensitivity analysis
- Automatic power transfer analysis
- Mode trace analysis
- Input data processing tool
- Easy to use graphical interface

All the functions used in this project include:

(1) Single-Machine-Infinite-Bus (SMIB) analysis

(2) Eigenvalue analysis within specified frequency and damping ranges

(3) Computation of modes closest to a specified frequency and damping

(4) Computation of modes related to a generator

(5) Time and frequency response calculations

(6) Mode trace

The text-based user interface for batch processing of SSAT is used to connect with PSS design/tuning optimization toolbox in MATLAB. As shown in Figure 3.39, SSAT is used to identify the state of power system that determines which modes require additional damping, as well as where PSS should be located. After identifying these results from SSAT, PSS design/tuning is implemented with MATLAB optimization toolbox. With the new designed/tuned PSS model, SSAT is also used to do frequency-domain verification to evaluate whether the system satisfies the performance requirement after PSS design/tuning.

3.7.2 Transient Security Assessment Tool – TSAT [38]

Non-linear effects, which are not considered in small signal analysis, may influence the PSS design/tuning results. In this project, Transient Security Assessment Tool – TSAT is used to investigate these effects to back up the small signal stability study. As widely used for stability analysis, TSAT employs non-linear models and step-by-step time simulation to accurately analyze the system behavior.

TSAT is a state-of-the-art tool for the transient security assessment (TSA) development and offers powerful features for both on and off-line applications. Its comprehensive analysis functions include:

1. Quick screening of contingencies so that only a small number of potentially critical contingencies have to be analyzed in detail.

2. Detailed time-domain simulation capable of processing large and complex power system models.
3. Availability of security indices to indicate the stability status of the system in terms of different criteria such as transient stability, small-signal stability, voltage stability, and frequency stability.
4. Determination of stability limits under a specified system condition.
5. An output analysis module that allows the detailed analysis of the simulation results.
6. A Fast Time-Domain (FTD) simulation module for use in conjunction with voltage security assessment tool (VSAT).

Its main features include:

- Comprehensive criteria definition
- Automatic contingency ranking
- Full time-domain simulation engine
- Multi-channel Prony analysis
- Early simulation termination
- Automatic power transfer limit determination
- Automatic fault impedance calculation

As shown in Figure 3.39, TSAT is used to do the time-domain simulation for large-signal performance verification of the designed/tuned PSS.

3.8 Factors Affecting PSS Design/Tuning

Effective damping contribution of a PSS depends upon many factors. Some of them are [43]:

- Type of excitation system
- Unit size (MVA) and unit inertia (H)
- PSS type
- Frequency of oscillation mode
- Location of the unit in the system

The way of these factors affecting PSS damping contribution can be different for different systems, and there are no absolute rules to follow. In this section, the effect of PSS construction, PSS type and excitation system type are discussed.

3.8.1 Effect of the Ramp-Tracking Filter

As the recommended type of new PSS, PSS2A (See Figure 2.5 and Figure 3.8) is widely used in industry practice. It is necessary to study the effect of its construction on the damping contribution.

As described in Section 2.2.2, to overcome problems experienced with torsional oscillation and power ramping, a special ramp-tracking filter is placed before the PSS main path (see Figure 2.5). Its corresponding function is defined by Equation 2-31. Here, a recommended time constant $T_9 = 0.1\ s$ is used to constitute the filter model in the form of $\left(\frac{1+0.4s}{(1+0.1s)^4}\right)^1$ [20]. The following result shows the important role of this ramp-tracking filter in the PSS performance.

In Figure 3.40, the phase of this filter has obviously lag characteristics attenuating the high frequency components (e.g. torsional components, measurement noise) from the incoming speed signal. However, with this phase lag, the phase of the equivalent speed deviation lags behind that of the speed deviation input, which is shown in Figure 3.42.

Thus, with this filter, the objective phase requires more phase lead compensation from PSS than without the filter.

To compare the PSS damping contribution with and without the ramp-tracking filter, a local mode with a damping of 4.9 % at a frequency of 1.315 Hz is considered separately with and without the filer. The tuned phase compensation of PSS is shown in Figure 3.43 and the tuned minimum gain is shown in Table 3.5.

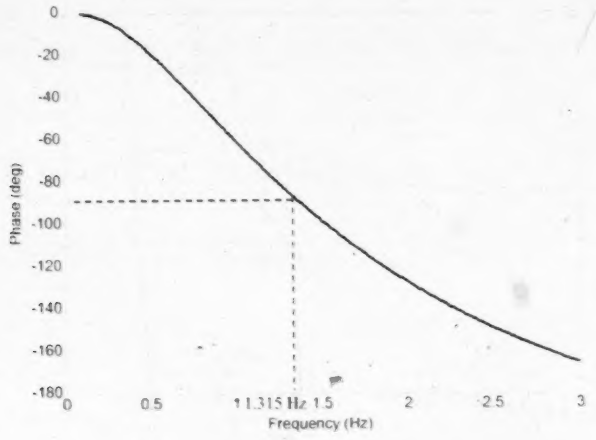


Figure 3.40 Phase characteristics of a ramp-tracking filter

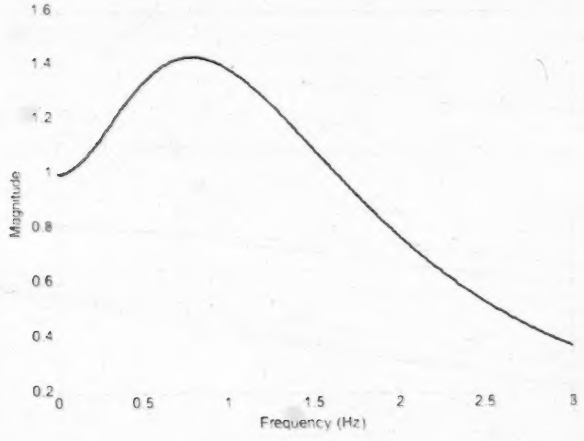


Figure 3.41 Magnitude characteristics of a ramp-tracking filter

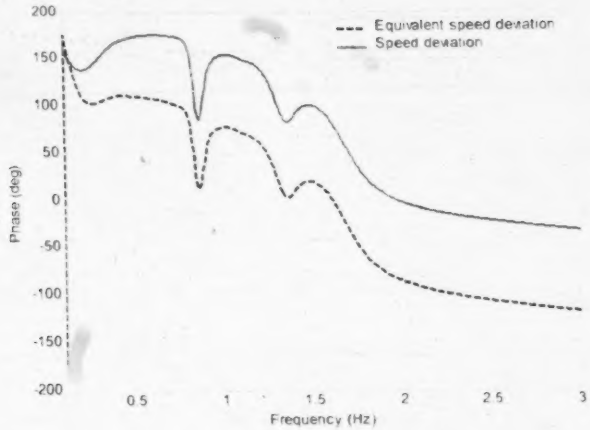


Figure 3.42 Phase characteristics of the speed deviation and equivalent speed deviation

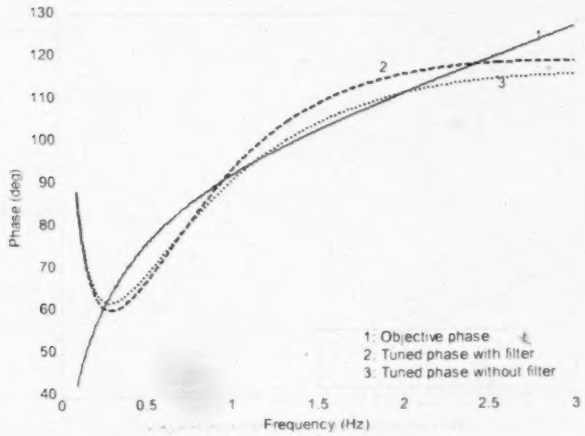


Figure 3.43 Phase characteristics of PSS with and without the ramp-tracking filter

Table 3.5 The tuned minimum gain with and without the ramp-tracking filter

Filter	Minimum Gain
With	25.9
Without	19.6

As it can be seen from Figure 3.43, compared to PSS having filter, the compatibility between the objective phase and tuned phase is better for a PSS without filter. However, the difference is small enough to be acceptable. For the tuned minimum gain, which is shown in Table 3.5, to satisfy the same performance requirement of an 8% damping, the minimum gain of PSS with filter is 25.9 exceeding 19.6, i.e., the minimum gain of PSS without a filter.

Therefore, the effect of ramp-tracking filter on dual input signal PSS should be taken into account when design/tuning this type of PSS. On one side, it adds some phase lag into the input signal, which requires much more phase compensation than on the situation without filter. On the other side, it reduces the magnitude of the tuned phase because the magnitude of filter is less than 1.0 in most of frequency range, as shown in Figure 3.41. Thus, PSS with the ramp-tracing filter requires a larger gain than PSS without the filter.

3.8.2 Effect of PSS Type

The type of PSS determined by input signals also have an effect on the PSS design/tuning result, as explained by the result shown in Figure 3.44 and Figure 3.45. Figure 3.44 shows the corresponding phase compensation characteristics, and Figure 3.45 shows the results of mode trace.

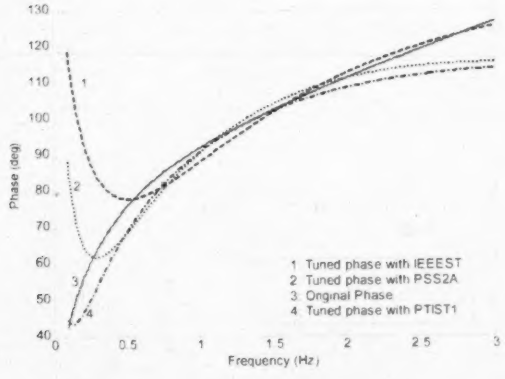


Figure 3.44 PSS phase characteristics for different PSS types

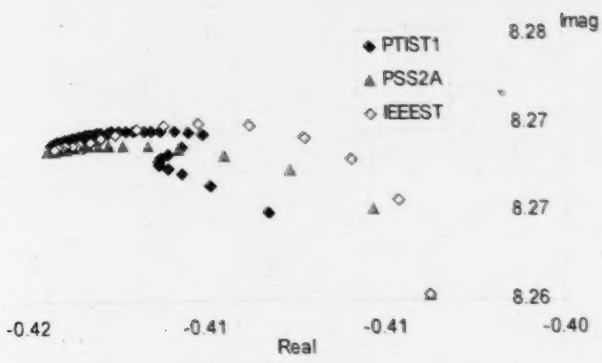


Figure 3.45 Mode trace for different PSS types

For the same PSS design/tuning objective and the same performance requirement, three types of PSS with different input signals, shown in Table 3.6 are designed/tuned.

Table 3.6 Tuned parameters of different type of PSS

PSS type	Input signal	Lead/Lag compensator	Minimum gain	Maximum gain
PTIST1	Speed	$1+0.09s\dfrac{1+0.45s}{1+0.03s}$	2.8	13
PSS2A	Speed and Electrical power	$\dfrac{1+0.21s}{1+0.02s}\dfrac{1+0.13s}{1+0.01s}$	19.6	30
IEEEST	Electrical power	$\dfrac{1+0.11s}{1+0.01s}\dfrac{1+0.11s}{1+0.5s}$	1.0	4.0

From the results tabulated in Table 3.6, it can be seen that parameters for PSS with different input signals may look very different while providing similar damping contribution. In Figure 3.44, comparing the tuned phase of these three types of PSS, one can find that with a speed input, the phase compensation of PTIST1 is well compatible with the objective phase. However, it is restricted to use a high gain value because of the stability of the exciter mode so that using this PSS is hard for a very poorly damped mode to satisfy the requirement. For IEEEST type of PSS, with a power input, the tuned gain is

free from the control mode, but the tuned phase has significant overcompensation at low frequencies, which may adversely affect the synchronizing torque. Compared with these two types of PSS with single input signals, PSS2A has the advantage of using both speed input and power input. The phase compensation does not have significant overcompensation in low frequency, and a considerably high value of the gain is acceptable with satisfying the performance requirement.

3.8.3 Effect of the Type of Excitation System

PSS may be used for damping system oscillations with any type of exciter: slow or fast; rotating or static. However, PSS are most effective in enhancing overall system stability when used with high initial response exciters, particularly thyristor exciters. Fast excitation response to generator terminal voltage variations, while contributing to improvement in transient stability, usually leads to degradation of system damping. With the addition of a properly designed PSS, system oscillations are well damped while utilizing the full potential of the excitation system for transient stability enhancement [28].

It is important to assess whether an excitation system is fast enough to be suitable for PSS design/tuning. However, no uniform criteria, which can define an excitation system's suitability for PSS, have been established so far. The reason is that there are some other factors such as size, capacity of the generator etc., which impact the behavior of excitation system. Thus, the performance of an excitation system depends on a particular unit in a particular environment. A benchmark system is suggested to assess the excitation system's suitability for PSS in Reference 35. However, it may be not applicable for the particular excitation system under study.

For these reasons, in this project, the following simple technical criteria are applied to assess an excitation system's suitability for PSS.

The excitation system is considered to be too slow to justify PSS installation if the objective phase between exciter input and electrical torque exceeds 180 degree. Conversely, if the objective phase is less than 180 degree, the excitation system is judged to be suitable for PSS considerations.

According to these criteria, Figure 3.46 shows the PSS phase compensation in a generator with a slow exciter. It can be seen that the objective phase exceeds 180 degree once the frequency is larger than 1.4 Hz. It indicates that the PSS phase should be lag over the frequency of 1.4 Hz, which is meaningless for the PSS design/tuning. Then, compromised phase compensation is obtained according to this objective phase. However, the verification results show that the small-signal performance of the target generator becomes worse with this tuned PSS. The reason is that for the local modes whose frequency is less than 1.4 Hz, the tuned PSS phase has almost no compensation; for the local modes with a frequency larger than 1.4 Hz, the tuned phase has significant overcompensation. Therefore, this excitation system is not suitable for PSS design/tuning.

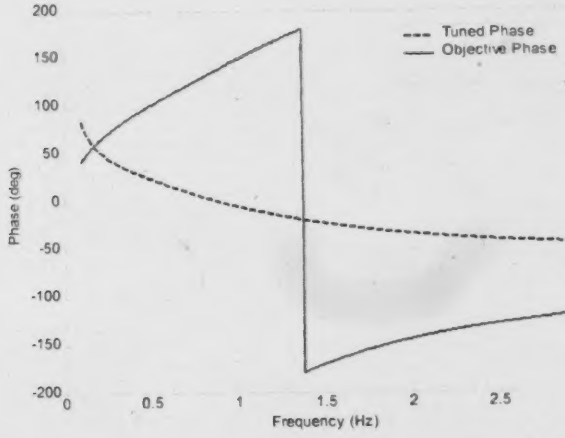


Figure 3.46 PSS phase characteristics with a slow exciter

In contrast to the slow exciter above, Figure 3.47 shows the PSS phase compensation with a fast exciter. With the objective phase less than 180 degree, a

compatible PSS phase characteristics is obtained. The verification results prove that the damping of the considered mode is improved with this tuned PSS.

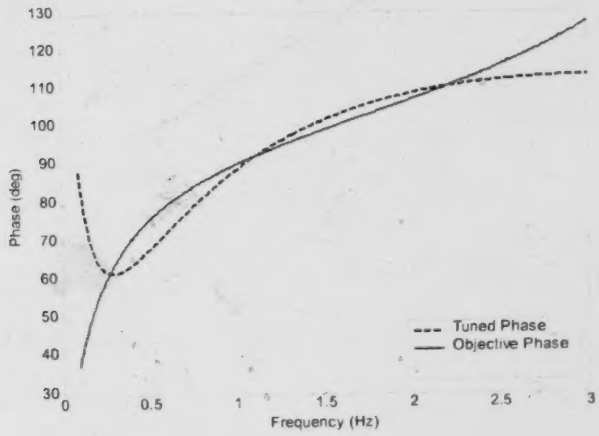


Figure 3.47 PSS phase characteristics with a fast exciter

Therefore, the type of excitation system has an important impact on the PSS design/tuning result. With older or slower acting exciter, it may not be possible to choose proper PSS parameters that improve damping unless one replaces the excitation system with a modern fast one. This consideration is beyond the topic of this thesis.

3.9 Conclusion

In this chapter, all the details of the proposed PSS design/tuning toolbox are described.

At the beginning of this chapter, the general approach of PSS design/tuning is described. Then all PSS types considered in this project are introduced. To design/tune PSS, it is important to choose the proper PSS location unless it is specified. When

design/tuning PSS for some specific modes, it is simple to use the participation factors to determine the placement of PSS.

The determinations of all stabilizer parameters are investigated, in particular the optimal tuning of time constants for lead/lag compensator, and gain tuning to provide a satisfied system performance. To provide flexible and optimal phase compensation, different phase constraints can be specified when setting time constants. For the gain tuning, the method of minimum gain setting depends on the PSS design/tuning objective, and the maximum gain is determined based on gain margin technique and field-testing.

This toolbox is designed using MATLAB optimization toolbox and two commercial software packages–SSAT and TSAT. SSAT is mainly used to perform all the computations related with the eigenvalue analysis and TSAT is used to verify the PSS design/tuning results.

There are some factors, which have an important effect on PSS design/tuning result. Besides the operation condition of power system, PSS design/tuning result is significantly influenced by PSS type, which is determined by input signals and construction, as well as the type of excitation system in the corresponding unit.

3.10 Issues Not Considered

There are two main issues not considered in this PSS design/tuning toolbox. One is the robustness problem caused by power system contingency. The other is the robust control design method for PSS design/tuning.

3.10.1 Robustness Problem

Power systems are nonlinear and consequently as the operating conditions change, so does the system dynamics. Hence, damping controllers should be robust enough to ensure that the oscillations are stable under all operating conditions.

For PSS design/tuning in this project, we do not consider contingencies involving large changes in system behavior under major structural changes, for example, when transmission lines are taken out of service for maintenance or to clear a system fault, or when a generator is not available. In these situations, power systems have to be stable for both small and large system changes.

At the same time, the robustness of PSS needs to be tested at two levels; one is the low-level robustness, which is considered as a standard step response. The other is in the performance verification of the system under a wide range of system conditions: changes in generation pattern, changes in transmission and changes in load. This should be implemented by users' specified contingency according to the considered power system.

3.10.2 Robust Controller Design

Conventional power system stabilizers designed on the basis of the phase compensation work well in the vicinity of the operating points for which they are designed. However, as this method relies on a linear design, there are some difficulties for the designed controller to maintain best damping performance because of the uncertainties in power system parameters and changing of operating conditions [45].

Since PSS should perform the desired function over the wide range of conditions encountered in the operation of the power system. As equipment models are known only approximately, PSS must have minimum sensitivity to parameters and characteristics of system elements. Therefore, to take into account of the changing system parameters, the stabilizer is required to be adaptive.

For this purpose, some other design methods such as adaptive stabilizer design based on optimization techniques have been, for some time, a major topic in control systems [10]. An adaptive stabilizer can perform better because it is capable of tracking and responding to the changing operating condition by providing a better match of the desired stabilizer characteristics, which may be affected by the operating condition. There are some reports on several optimization techniques currently being used in power system dynamics and control [4]. Although these methods are still constraint by some practical considerations for industry implementation, this is an area of considerable potential, and applications in power system controller design are increasing.

Chapter 4

Case Studies

The goal of this chapter is to demonstrate the performance of the proposed PSS design tuning toolbox. For this purpose, two cases will be studied.

4.1 Case1

4.1.1 Case Introduction

This case is based on a realistic system model with 470 buses and 45 generators. The system includes 4 existing PSS, which are located respectively, in BUS11, BUS102, BUS701 and BUS831. The single line diagram of the system, which includes a 345 KV network and the major generation sites, is shown in the Appendix C.

4.1.2 Preliminary Analysis

The results from SSAT eigenvalue scan between 0.1 Hz to 3.0 Hz shows that this system has an inter-area mode at frequency around 0.83 Hz, and the corresponding damping is around 3.15%. The oscillation is between area 1 and area 2 in the base case condition. All the other modes between 1.0 Hz and 3.0 Hz are local ones, which are reasonably damped at the base case condition with damping exceeding 4%. All the eigenvalues of these oscillation modes are given in Table 4.1.

Table 4.1 Eigenvalues of modes between 0.1 Hz and 3.0 Hz with base case condition

Mode No.	Real	Imaginary	Frequency (Hz)	Damping (%)
1	-0.1654	5.2455	0.8348	3.15
2	-0.3298	6.8011	1.0824	4.84
3	-0.4168	8.2667	1.3157	5.04
4	-0.3992	7.8298	1.2462	5.09
5	-0.3786	7.4003	1.1778	5.11
6	-0.3946	7.4581	1.187	5.28
7	-0.555	9.374	1.4919	5.91
8	-0.6772	10.0858	1.6052	6.7
9	-0.6062	8.9917	1.4311	6.73
10	-0.7058	10.1107	1.6092	6.96
11	-0.6538	9.118	1.4512	7.15
12	-0.7601	10.4829	1.6684	7.23
13	-0.707	9.6934	1.5427	7.27
14	-0.6837	9.3085	1.4815	7.33
15	-0.5974	8.1195	1.2923	7.34
16	-0.7878	10.2893	1.6376	7.63
17	-0.7878	10.2068	1.6245	7.7
18	-0.7119	9.019	1.4354	7.87
19	-0.9345	11.2507	1.7906	8.28
20	-1.0146	11.0843	1.7641	9.12
21	-1.1289	12.185	1.9393	9.22
22	-0.7803	7.9615	1.2671	9.75

To gain a better understanding of the system behavior, we will consider 73 contingencies of all 345KV single line outages applied to the base case. The eigenvalue scan results of SSAT show that the oscillation modes are less damped with these contingencies compared to the base case. Table 4.2 shows the top 11 critical contingencies, which worsen the damping of the inter-area mode. According to the single line diagram, one can see that these top 11 contingencies include all the connection line outages between area 1 and area 2. This fact may explain why these contingencies have an important effect on the considered inter-area mode.

Table 4.2 Eigenvalue of the inter-area mode with different contingencies

Mode No.	Real	Imaginary	Frequency (Hz)	Damping (%)	Outage line (BUS No., ID)
1	-0.108	4.8183	0.7669	2.24	2490-2660,1
2	-0.1177	5.0016	0.796	2.35	2490-2500,1
3	-0.1345	4.9867	0.7937	2.7	2500-2660,1
4	-0.1359	4.9855	0.7935	2.72	2500-2650,1
5	-0.1359	4.9855	0.7935	2.72	2500- 2650,2
6	-0.1481	5.1734	0.8234	2.86	1000-2650,1
7	-0.1517	5.1684	0.8226	2.93	2650-2950,1
8	-0.1534	5.1733	0.8234	2.96	2660-2900,1
9	-0.1534	5.1733	0.8234	2.96	2660-2900,2
10	-0.1553	5.1848	0.8252	2.99	1080-2650,1
11	-0.1553	5.1848	0.8252	2.99	1080-2650,2

Results also show that for the local modes, only mode No. 2 in Table 4.1 has a damping less than 5% with base case condition. However, in the situation of contingencies, a total of 102 lightly damped local modes with a damping less than 5% are found.

To confirm the effect of contingency on the oscillation mode, a time domain simulation is employed with the No.1 contingency listed in Table 4.2. Figure 4.1 shows the response of generator speed in BUS 9101, which has the largest participation factor of the inter-area mode. It is found that the oscillation magnitude of the generator speed is larger when the contingency occurs compared to that without contingency. So, under the situation of contingencies, the transient stability of the system is worse than for the base case condition.

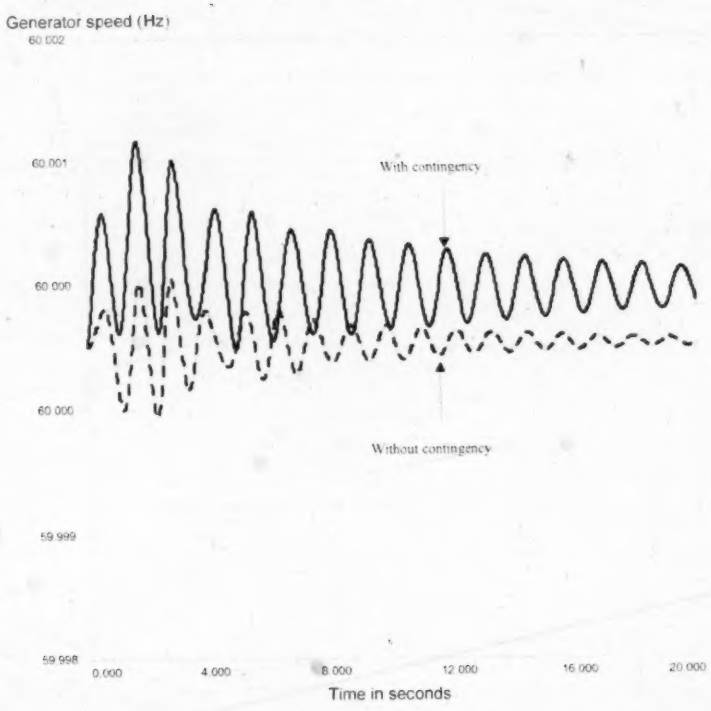


Figure 4.1 Time-domain simulation of generator speed with and without contingency

Thus, in addition to the poorly damped oscillation modes in base case condition, both the small signal stability and the transient stability deteriorate to threaten the system stable operation under large disturbances. To improve the oscillation damping for the small signal stability and provide sufficient transient stability, it is necessary to design or tune PSS for this system.

4.1.3 PSS Design/Tuning Objective and Process

The PSS design/tuning objective is to improve the performance of the poorly damped inter-area mode. The tuning process is done according to flow chart introduced in Section 3.6. For the PSS design/tuning for inter-area mode, it includes the following main steps:

Step1: Run SSAT to find the inter-area mode.

Step2: Identify the generators that have PSS and are the relatively effective in controlling the inter-area mode. Such generators have a participation factor larger than 0.2.

Step3: For reference, also find the local modes of these generators without PSS in service to determine the mode-list of the considered generators.

Step4: For the target unit, compute the frequency response between the reference voltage of exciter and electrical torque when the generator inertia is increased by a factor of 1000 times compared to the original value. At the same time, set all the other generators as infinite buses to eliminate their effects on the target generator.

Step5: Tune the time constant parameters of the target PSS to find the appropriate phase compensation.

Step6: Modify the PSS parameter with the tuned new time constants.

Step7: Gradually increase the PSS gain until the gain margin is found in the basis of the first unstable mode or it reaches the gain limit. The maximum gain is determined by the gain margin or the gain limit.

Step8: Trace the target inter-area mode with different PSS gain to find the minimum gain, which makes the inter-area mode satisfy the performance requirement.

Step9: Observe the mode trace plot from step 8 and determine the optimal maximum gain.

Step10: Verify the tuned parameters by calculation of the gain matrix performance in frequency-domain, and time-domain simulation, which includes a standard step response and specified contingencies.

4.1.4 Results Analysis

To design/tune PSS for the considered inter-area mode, some default tuning parameters and requirement are set as follows:

(1) Performance requirement is a minimum damping of 5%.

(2) Limits on the compensator time constants are from 0.01 second to 0.5second.

(3) Limits on the default washout time constants are from 1 second to 3 second.

(4) Default washout time constant is 2 second.

(5) Frequency range considered is from 0.1 Hz to 3 Hz.

(6) Limits on the gain are from 0.1 to 30.

According to the participation factor of the considered inter-area mode, the candidate machines for controlling this mode are listed in Table 4.3.

Table 4.3 Candidate machine list for controlling the inter-area mode

Generator No.	BUS No.	ID	PSS type	Exciter type	Participation factor
1	9101	1	No PSS	EXST1	1.0000
2	1001	1	No PSS	EXAC3	0.9151
3	1104	4	No PSS	IEEET1	0.8433
4	102	2	PTIST1	EXAC1	0.6507
5	11	1	PTIST1	IEEET1	0.5774
6	101	1	No PSS	IEEET1	0.5397
7	9103	1	No PSS	EXST1	0.4774
8	616	4	No PSS	SCRX	0.4522
9	1103	3	No PSS	IEEET1	0.3556
10	223	1	No PSS	IEEET3	0.3394
11	1085	1	No PSS	EXAC4	0.2902
12	1101	1	No PSS	IEEET1	0.2834
13	1091	1	No PSS	EXAC4	0.2827
14	222	2	No PSS	IEEET1	0.2778
15	531	1	No PSS	EXAC3	0.2644
16	1201	1	No PSS	IEEET3	0.2640

As shown in Table 4.3, there is a total of 16 generators related to the considered mode with a participation factor larger than 0.2. Among them, except for two existing PSS in BUS102 and BUS11, all the others have an exciter and thus can be available for adding new PSS. To damp the target inter-area oscillation mode, the following different situations are analyzed and compared according to the candidate generators listed in above table.

4.1.4.1 Tune Existing PSS

In this situation, only two existing PSS are tuned, which include the PSS in generator of BUS11and BUS102 respectively. The considered type of PSS is PTIST1, and the corresponding diagram is shown in Figure 3.6.

Step1. Parameters determination

1. **Determination of time constants**

For each PSS, the considered time constants (See Table 3.1) and gain (See Figure 3.14) are tuned. Figure 4.2 and Figure 4.3 show the comparison of PSS characteristics between the objective phase, original phase and tuned phase. Table 4.4 shows all the results of the tuned time constants.

In Figure 4.2, compared with the original PSS phase shown by curve 3, which has a maximum overcompensation around 10 degree between 0.7 Hz to 1.9 Hz, the tuned phase has only a small under compensation caused by the practical constraint, which specifies that the maximum compensator phase is 120 degree. Thus, the phase characteristics of the tuned PSS are more preferable.

In Figure 4.3, curve 3 shows that the original PSS phase has a considerable overcompensation all over the frequency range considered, which has an undesirable

effect on the synchronizing torque, especially for damping the inter-area mode. However, after this PSS is tuned, curve 1 shows much improvement of the phase characteristics.

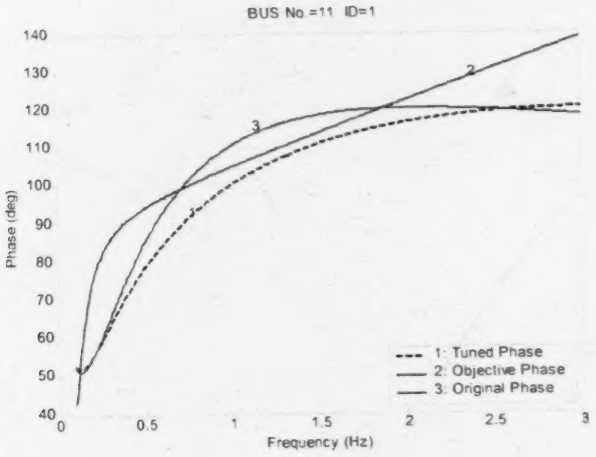


Figure 4.2 Phase characteristics of PSS in BUS11

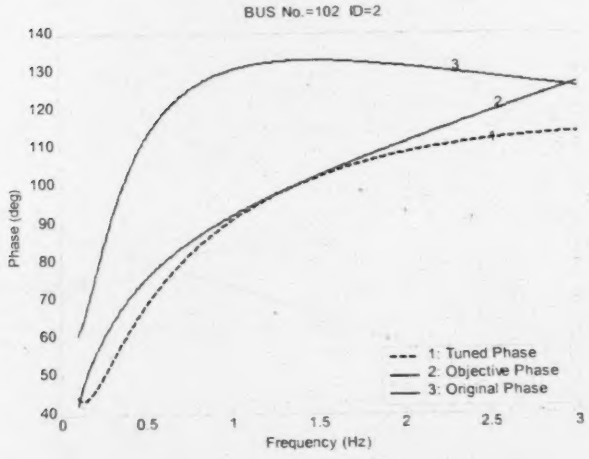


Figure 4.3 Phase characteristics of PSS in BUS102

Table 4.4 Time constants of the tuned PSS

	Original Parameters		New Parameters	
PSS	Washout	Lead/Lag Compensator	Washout	Lead/Lag Compensator
BUS11	$\frac{2.5s}{(1+2.5s)}$	$(1+0.3s)\frac{(1+0.3s)}{(1+0.05s)}$	$\frac{2.5s}{(1+2.5s)}$	$(1+0.09s)\frac{(1+0.45s)}{(1+0.03s)}$
BUS102	$\frac{3.0s}{(1+3.0s)}$	$(1+0.5s)\frac{(1+0.5s)}{(1+0.05s)}$	$\frac{3.0s}{(1+3.0s)}$	$(1+0.09s)\frac{(1+0.41s)}{(1+0.03s)}$

Therefore, for both tuned PSS, the new phase fits the objective phase better than before PSS tuning.

Figure 4.4 shows the mode trace of the time constant tuning process while the gains remain constant. With the considered mode shifting to the right in s-plane, one can notice that the damping becomes smaller by only tuning the time constants. The reason is that the original PSS phase with overcompensation is mitigated after the time constants are tuned, which are shown in Figure 4.2 and Figure 4.3, especially for PSS in BUS102.

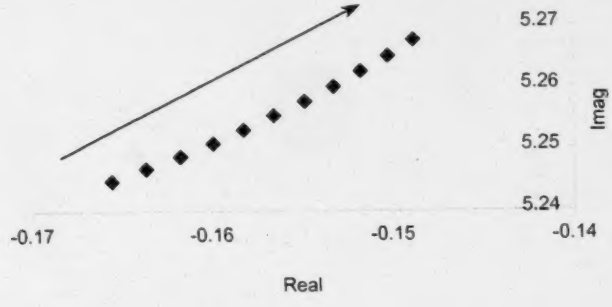


Figure 4.4 Mode trace about time constants tuning

Even though the original time constants with overcompensation phase characteristics provide a larger damping than that of the new ones, according to Section 3.5.1.2, it is known that overcompensation results in a negative synchronizing torque,

which will have an adverse effect on the transient stability. PSS with new time constants solve this problem by providing a positive synchronizing torque. This can be proved by the results in Figure 4.5, which shows the time-domain simulation of generator in BUS102 under the No.1 contingency of Table 4.2.

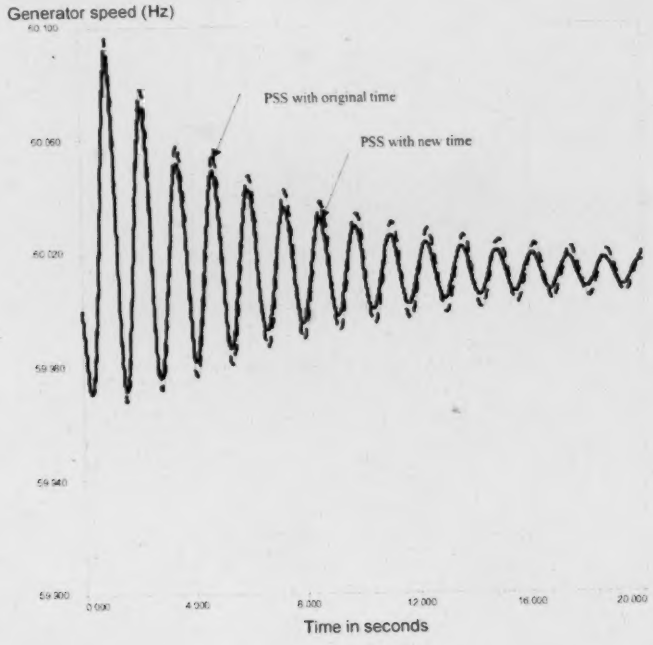


Figure 4.5 Generator speed with different time constants of PSS

2. Determination of gain

The following mode trace plot is for PSS gain determination. In Figure 4.6, as gains increase, damping of the considered inter-area mode increases until the performance requirement of 5% is achieved, thus, the corresponding minimum gain is determined as 9.4. Based on the approach described in Section 3.5.2.3, a maximum gain of 13.4 is determined for both PSS.

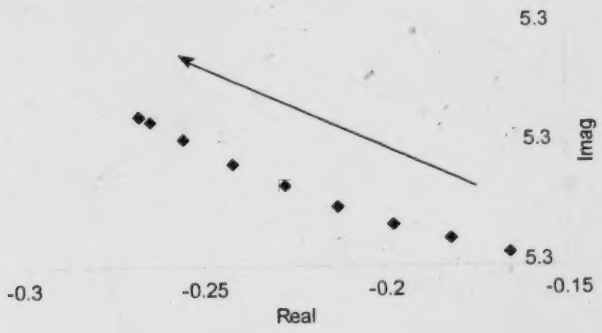


Figure 4.6 Mode trace with gain tuning

Step 2. Gain performance matrix

With the tuned time constants of PSS, the following table shows the eigenvalue matrix of the considered inter-area mode for various gain values.

Table 4.5 Damping of the inter-area mode for various gain values

Gain	9.4	11.4	13.4
Damping (%)	5.0	5.5	5.8

Step 3. Performance verification

The small-signal performance can be easily proved by observing above gain performance matrix in Table 4.5. The damping of the considered inter-area mode is improved with the tuned PSS.

To verify the large signal performance of PSS with the new parameters, for each target generator, a standard step response with 5% disturbance in the reference voltage of the exciter is applied. The time-domain response for the candidate generators obtained from TSAT are shown in Figure 4.7 and Figure 4.8.

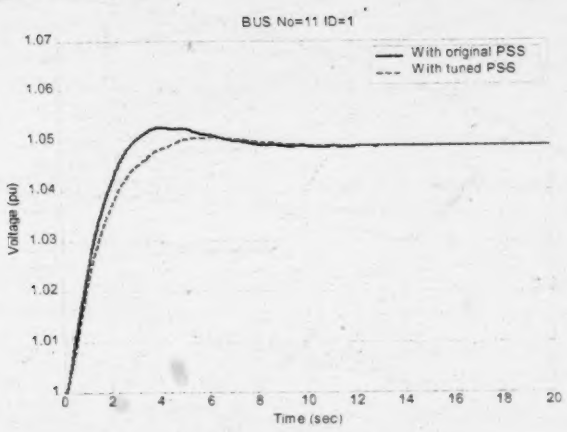


Figure 4.7 Step response for generator in BUS11

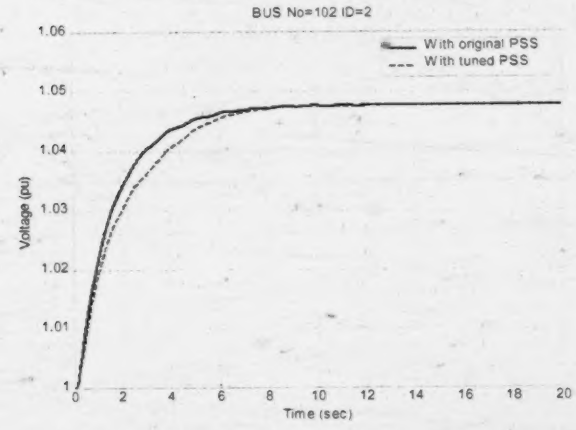


Figure 4.8 Step response for generator in BUS102

According to description of section 2.2.4, the corresponding performance index of above step response is shown in Table 4.6.

Table 4.6 Step response indices for generator in BUS11 and BUS102

Generator	BUS11		BUS102	
Index	Original	New	Original	New
Setting time (second)	1.99	2.59	3.53	4.50
Overshoot (%)	0.36	0.17	0.0	0.0
Rise time (second)	1.87	2.26	2.52	3.32

From the above indices of the step response, it is easily found that the dynamic characteristics of generators with new PSS is better than that of original ones, with the tuned PSS overshoot is less prominent. Rise time has a little change. Although setting time with the tuned PSS is a little longer than that with the original PSS, it is fast enough to be acceptable. Therefore, the PSS tuning results in improvement of the transient performance under a small disturbance.

To test the robustness of the tuned PSS in overall system behavior, the next verification focused on the damping provided by the tuned PSS in response to a transient fault condition. This verification will demonstrate the stable operation of the tuned PSS under major disturbances of the system. The contingency involves a three phase fault in BUS2660 when time equal to 50 cycles, and fault is cleared 5 cycles later by opening both ends of the faulted circuit from BUS2660 to BUS2490 simultaneously, which is one of the main connection lines between two oscillation areas [Appendix C]. The simulations compare the response of the generators with the existing PSS and that with the tuned PSS. The plot of active power of candidate generators is shown in Figure 4.9 and Figure 4.10. Obviously, the dynamic characteristics are improved after PSS tuning.

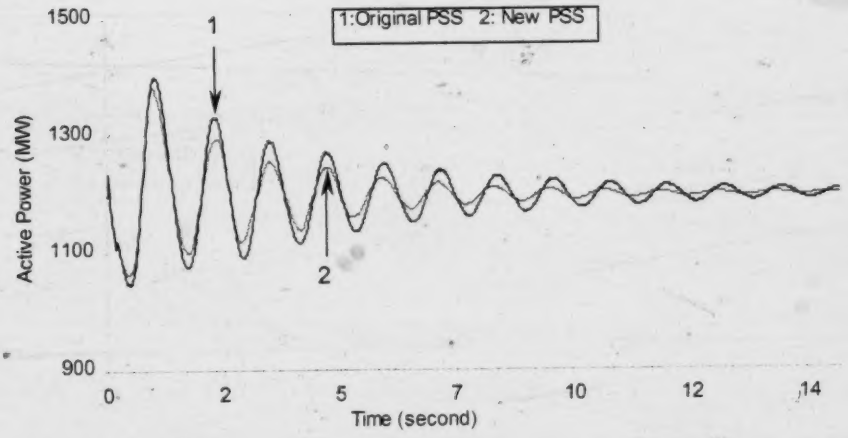


Figure 4.9 Time-domain simulation of generator in BUS11 with contingency

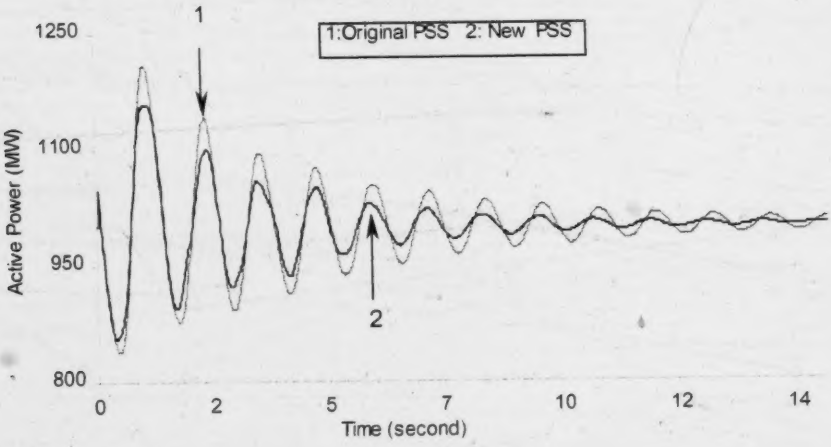


Figure 4.10 Time-domain simulation of generator in BUS102 with contingency

The following plot shows the damping contribution of the tuned PSS by comparing the mode location between the original PSS and that of the tuned PSS.

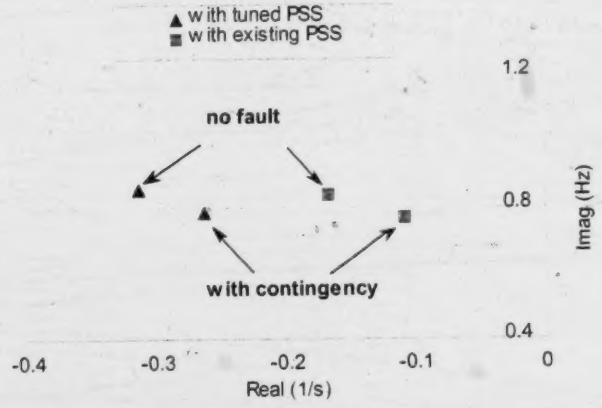


Figure 4.11 Eigenvalue of the inter-area mode with and without PSS tuning

In Figure 4.11, with the tuned PSS, not only for no fault case, but also in the contingency situation, damping of the tuned mode moved farther to left in s-plane compared to the damping of existing PSS. With a maximum gain of the tuned PSS, the

damping ratio in the no fault situation is improved from 3.15% to 5.84%, and that in the contingency situation is also improved from 2.24% to 5.36%. And the frequency of the target mode with the tuned PSS is slightly higher than the situation with the original PSS, this rise is another explanation of the increasing of synchronizing torque due to the tuned PSS.

Therefore, the verification of both small-signal and large-signal performance demonstrates that the tuned PSS improve damping and synchronizing torques for the concerned inter-area mode. The improvement in damping torque is characterized by an increase in the damping while improvements in synchronizing torque result in improvement of the system transient behavior.

Compared with above results, where all the considered parameters are tuned, in some particular cases, only a part of PSS parameters can be available for adjusting. To compare the results, the following two situations are investigated.

- Only time constants of the PSS are tuned. The same phase compensation is obtained as in Figure 4.2 and Figure 4.3. However, without gain tuning, the inter-area mode does not satisfy the performance requirement.

- Only PSS gain is tuned. Results show that, in order to satisfy the required damping of 5%, the minimum gain of both tuned PSS is 4.0, which is less than 9.4 shown in Table 4.5. This can be explained by the phase overcompensation of the original PSS.

4.1.4.2 Design New PSS

In this section, only the generators without PSS but with an exciter are considered. New PSS can be added into these generators. Totally there are 14 generators are available for new PSS design, which are listed in Table 4.3 except for generator No.4

and No.5, which have been equipped with PSS. As mentioned in Section 3.6, PSS2A is the recommended type for new PSS design.

In industry applications, it is neither economical nor practical to add new PSS to all the candidate generators at one time. A better approach is to examine the effort of progressing installation of new PSS. The sequence of adding new PSS is determined by the corresponding participation factor value, which is shown in Table 4.3. The larger the participation factor, the more effective will be the generator control of the inter-area mode. Therefore, it is natural to consider the installation of new PSS in this generator first. To satisfy the performance requirement of a 5% minimum damping, different minimum gain value is determined when different number of new PSS is designed. The corresponding result is shown in Table 4.7.

Table 4.7 Different gain with different number of new PSS

New PSS No.	BUS of new PSS	PSS minimum gain
1	9101	24.7
2	9101, 1001	7.9
3	9101, 1001, 1104	4.3

In Table 4.7, if only one new PSS is added in BUS9101, a relatively high minimum gain with the value of 24.7 is determined to make the considered inter-area mode satisfy the performance. When two PSS are added, under the same performance requirement, the corresponding minimum gain decreases to a small value of 7.9. Therefore, the more new PSS are added, the smaller the determined minimum gain because all the added new PSS share the controllability of the considered inter-area mode. Study shows that the minimum gain is only 1.9 if all the candidate generators in Table 4.3 are equipped with new PSS. Obviously, the potential of all PSS is so small that this action is not cost effective for PSS behavior. Generally, new PSS are only considered for several generators, which have high participation factors for the considered mode.

4.1.4.3 PSS Design and Tuning

In this section, all the generators in the candidate list of Table 4.3 are handled, which includes the tuning of existing PSS and the design of new PSS.

Figure 4.12 shows the mode trace of the parameter determination process for all considered PSS. The damping of the considered inter-area mode is apparently improved with the PSS design/tuning.

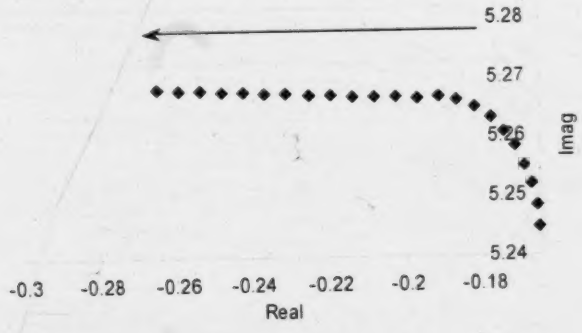


Figure 4.12 Mode trace of the inter-area mode for PSS design/tuning

To observe the effect of the designed/tuned PSS on the overall system performance, eigenvalue spectra of all the oscillation modes between 0.2 Hz and 2.0 Hz are analyzed.

Figure 4.13 shows the eigenvalue spectrum with all the original PSS, where there are two poorly damped modes with damping less than 5%. Figure 4.14 shows the eigenvalue spectrum when all PSS were removed from the system, which result in five modes with damping less than 5%. Compared with these two situations, Figure 4.15 shows that all these poorly damped oscillation modes are mitigated after PSS design/tuning. In Figure 4.15, no eigenvalue has damping below 5 %. Figure 4.16 shows the comparison of the corresponding damping.

The eigenvalue spectra pictured in these figures clearly demonstrate the large improvements in system oscillation damping brought by PSS design/tuning.

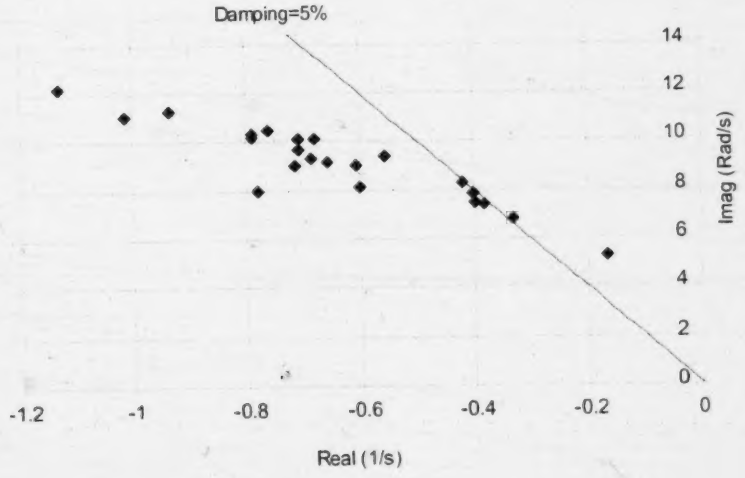


Figure 4.13 Eigenvalue spectrum with the original PSS

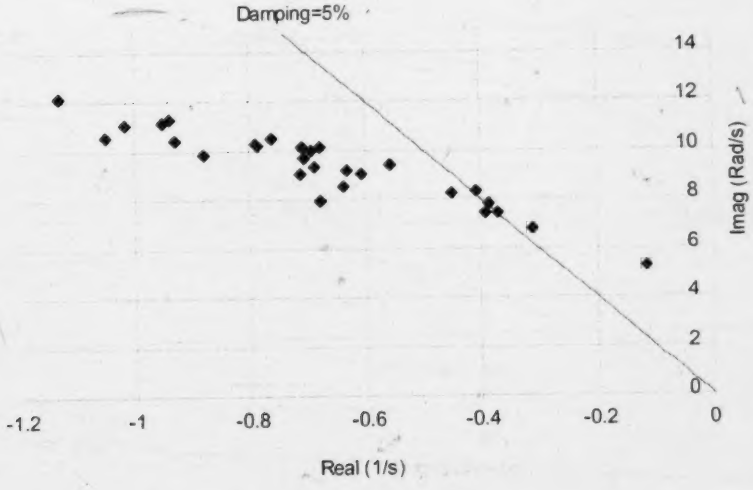


Figure 4.14 Eigenvalue spectrum without any PSS

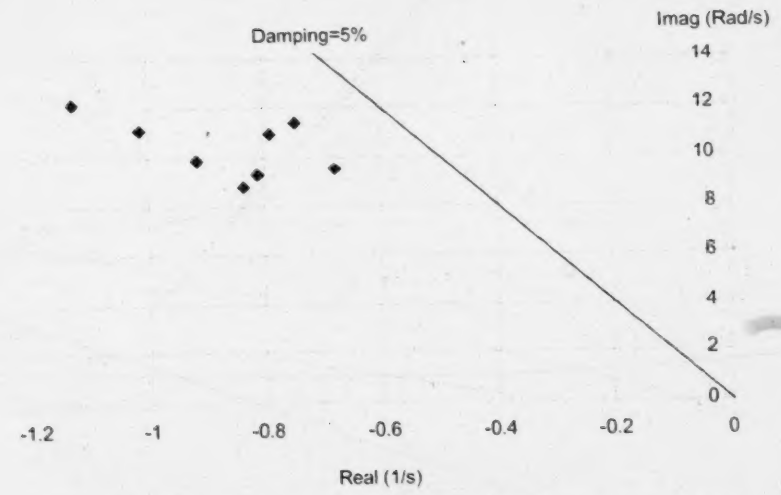


Figure 4.15 Eigenvalue spectrum with the designed/tuned PSS

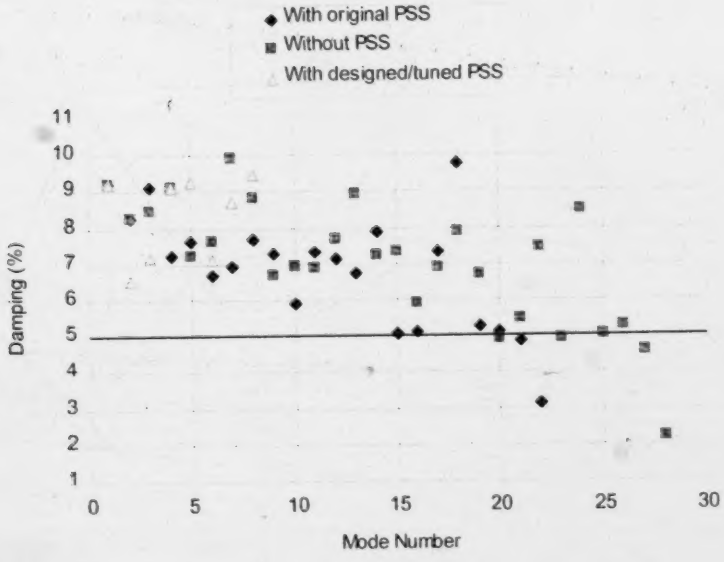


Figure 4.16 Damping comparison of modes within 0.2 Hz to 2.0 Hz

4.2 Case2

4.2.1 Case Introduction

The model used in this case is a loose representation of the south and east boundary of the U.S.-Canada interconnected power system, which is schematically shown in Figure 4.17. The whole system shown in Figure 4.17 represents the North American electric system, which includes ten regional memberships of the North American Electric Reliability Council (NERC): ECAR; ERCOT; FRCC; MAAC; MAIN; MAPP; NPCC; SERC; SPP; and WSCC. Except for WSCC and ERCOT, all the other regions constitute the system model used in this case, which is a large and complex power system including 39872 buses and 4293 generators.

Figure 4.17 Southeast interconnected system of NERC

4.2.2 Preliminary Analysis

This system exhibits many oscillations modes. The modes listed in Table 4.8 were computed by SSAT using an eigenvalue scan between 0.1 Hz and 1.0 Hz. Most of the modes in Table 4.8 are inter-area. Modes No.16 to No.74 have a damping above 3%, and are of little interest for the present study. The poorly damped local modes of each generator to be considered will be identified by SSAT using the computation of modes related to a generator.

In this case, the analysis of the inter-area mode and local mode only focuses on the base case; the contingency arising under a disturbance is not to be considered.

Table 4.8 Eigenvalues of oscillation modes between 0.1 Hz and 1.0 Hz

Mode No.	Real	Imaginary	Frequency (Hz)	Damping (%)
1	0.0796	1.0677	0.1699	-7.43
2	-0.0448	5.5115	0.8772	0.81
3	-0.059	5.4318	0.8645	1.09
4	-0.0458	3.6499	0.5809	1.26
5	-0.0501	3.9457	0.628	1.27
6	-0.054	4.0862	0.6503	1.32
7	-0.086	6.0454	0.9621	1.42
8	-0.0829	5.7431	0.914	1.44
9	-0.1131	6.0414	0.9615	1.87
10	-0.0651	2.8496	0.4535	2.28
11	-0.1347	5.5343	0.8808	2.43
12	-0.154	5.73	0.912	2.69
13	-0.1309	4.8676	0.7747	2.69
14	-0.1538	5.38	0.8563	2.86
15	-0.1815	6.1327	0.9761	2.96
16	-0.0978	3.2094	0.5108	3.05
17	-0.1765	5.6657	0.9017	3.11
18	-0.172	5.5221	0.8789	3.11
19	-0.153	4.8069	0.765	3.18
20	-0.1764	5.5055	0.8762	3.2
21	-0.1378	4.2522	0.6768	3.24
22	-0.1497	4.5829	0.7294	3.27
23	-0.1816	5.4892	0.8736	3.31
24	-0.1645	4.9282	0.7843	3.34
25	-0.1738	5.1788	0.8242	3.35
26	-0.1765	5.0765	0.8079	3.48
27	-0.1289	3.6893	0.5872	3.49
28	-0.2032	5.7376	0.9132	3.54
29	-0.0914	2.548	0.4055	3.58
30	-0.1697	4.7211	0.7514	3.59
31	-0.2294	6.2654	0.9972	3.66
32	-0.2047	5.504	0.876	3.72
33	-0.2283	6.1165	0.9735	3.73
34	-0.1995	5.2735	0.8393	3.78
35	-0.235	6.0782	0.9674	3.86

Table 4.8 Eigenvalues of oscillation modes between 0.1 Hz and 1.0 Hz (continued)

Mode No.	Real	Imaginary	Frequency (Hz)	Damping (%)
36	-0.213	5.3881	0.8575	3.95
37	-0.2186	5.4354	0.8651	4.02
38	-0.1913	4.5331	0.7215	4.22
39	-0.1723	3.7976	0.6044	4.53
40	-0.2822	6.1122	0.9728	4.61
41	-0.23	4.9695	0.7909	4.62
42	-0.2929	6.2092	0.9882	4.71
43	-0.2541	5.3229	0.8472	4.77
44	-0.0959	2.0079	0.3196	4.77
45	-0.2084	4.3537	0.6929	4.78
46	-0.2792	5.8123	0.9251	4.8
47	-0.248	5.0664	0.8063	4.89
48	-0.2898	5.8776	0.9355	4.92
49	-0.2662	5.3485	0.8512	4.97
50	-0.3033	6.0945	0.97	4.97
51	-0.2908	5.71	0.9088	5.09
52	-0.3043	5.9454	0.9462	5.11
53	-0.251	4.8975	0.7795	5.12
54	-0.284	5.5171	0.8781	5.14
55	-0.2431	4.6644	0.7424	5.21
56	-0.3015	5.7328	0.9124	5.25
57	-0.3447	5.9593	0.9484	5.77
58	-0.3538	5.98	0.9518	5.91
59	-0.3812	6.2437	0.9937	6.09
60	-0.1953	3.1441	0.5004	6.2
61	-0.3768	5.8617	0.9329	6.42
62	-0.361	5.536	0.8811	6.51
63	-0.3773	5.6035	0.8918	6.72
64	-0.1693	2.4885	0.3961	6.79
65	-0.3091	4.5254	0.7202	6.81
66	-0.4455	5.9849	0.9525	7.42
67	-0.4427	5.8406	0.9296	7.56
68	-0.4803	6.1764	0.983	7.75
69	-0.1151	1.432	0.2279	8.01
70	-0.1462	1.8068	0.2876	8.07
71	-0.2522	3.0109	0.4792	8.35
72	-0.3058	3.3902	0.5396	8.98
73	-0.3964	4.1601	0.6621	9.48
74	-0.6109	6.1175	0.9736	9.94

4.2.3 System Configuration

To simplify the system, all the generators in service are classified according to Table 4.9.

Table 4.9 Classification of generators

With Exciter and with PSS	With Exciter but without PSS	Without exciter and without PSS	Total
319	3096	878	4293

The requirements for PSS design/tuning are summarized as follows:

- New PSS are only considered for generators larger than 50 MVA because installing new PSS into the small generators is not cost effective. Among all 3096 generators with an exciter but without PSS, totally there are 2365 generators with capacity above 50 MVA available for new PSS installation.

- The PSS design/tuning should improve the damping of two objectives, i.e., inter-area modes and local modes.

- Avoid adverse interaction between different PSS design/tuning objectives.

- Separate performance criteria will be used for the local modes and inter-area modes.

4.2.4 Performance Analysis

4.2.4.1 PSS Design/Tuning for Specified Generators

In this task, PSS is designed/tuned for the poorly damped local modes of the specified generators. The generators to be considered include both retuning existing PSS

and adding new PSS. The total number of PSS to be considered is 2684, which includes 319 existing PSS to be tuned and 2365 new PSS to be added. The statistic information of the considered PSS is tabulated in Table 4.10.

Local modes of all 2684 generators are scanned individually using SSAT. According to Table 4.10, 294 candidate generators, which have poorly damped local modes with a damping less than 5%, are identified. These units are the candidate generators for PSS design/tuning. Among all candidate generators, 268 generators should be equipped with new PSS and 26 generators should be tuned with the existing PSS. For the new PSS to be added, as mentioned in Section 4.1.4.2, PSS2A with speed deviation input and electrical power input is used as the recommended PSS (See Figure 3.8).

Table 4.10 Statistic information of PSS to be added or tuned

PSS type	PSS number	Candidate generators	Generators unsuitable for new PSS	Target generator
New PSS	2365	268	72	196
Existing PSS	319	26	11	15
Total	2684	294	83	211

The excitation system's suitability for PSS should be investigated for each candidate generator [45]. According to the simple technical criteria defined for assessing an excitation system's suitability for PSS introduced in Section 3.8.3, generators with an excitation system unsuitable for the installation of new PSS are identified and dropped from the candidate generator list. Thus, at the end there are 211 PSS to be considered, which include 196 PSS to be added and 15 PSS to be tuned.

For these 211 target generators, PSS will be designed/tuned using the proposed approach in this project so that the corresponding target poorly damped local modes

satisfy the performance requirement, which is specified as a minimum damping of 5%. Then, to verify the small-signal performance of all designed/tuned PSS, all new modes related to each target generator will be computed by SSAT. Table 4.11 lists the comparison of local modes in different damping range with and without PSS design/tuning. Figure 4.18 to Figure 4.20 show the results of damping comparison, where "New" refers to the situation with PSS design/tuning, while "Original" refers to the situation without PSS design/tuning.

Table 4.11 Comparison of local modes with and without PSS design/tuning

Damp range	Range 1	Range 2	Range 3	Range 4	Range 5	Range 6	Range7	Range 8	Total
Damp (%)	-1% to 0	0 to1%	1% to 2%	2% to 3%	3% to 4%	4% to 5%	<5%	>5%	<100%
Original modes	1	13	10	19	69	150	262	171	433
New modes	0	0	0	2	1	12	15	325	340

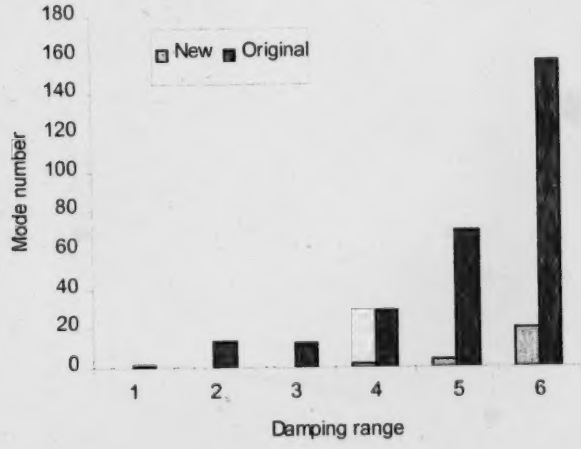


Figure 4.18 Comparison of the target mode number with and without PSS design/tuning

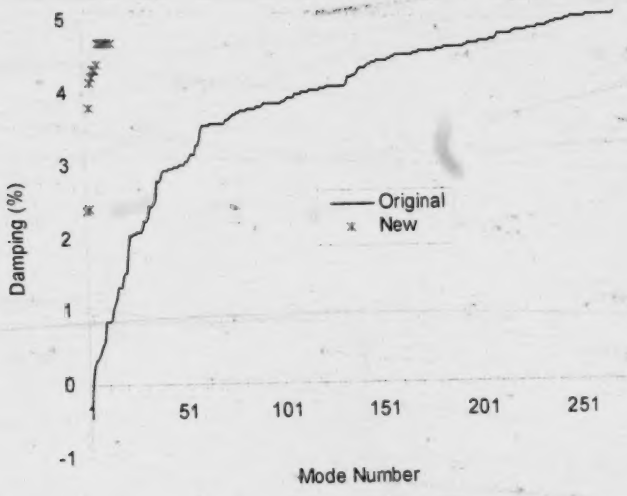


Figure 4.19 Comparison of the damping of target modes with and without PSS design/tuning

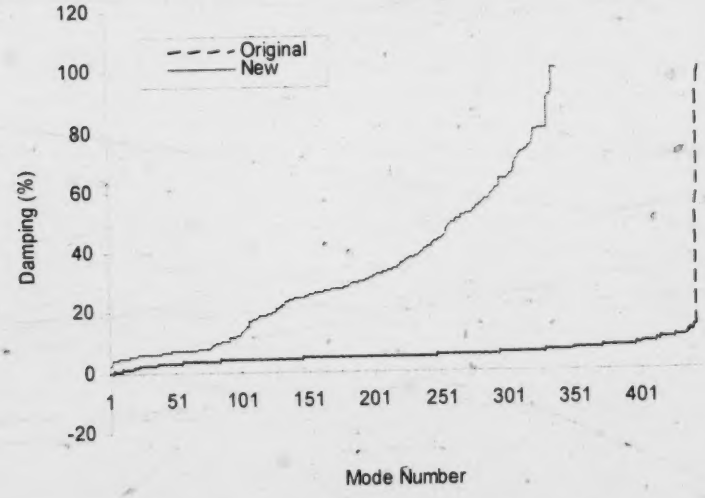


Figure 4.20 Comparison of the damping of all local modes with and without PSS design/tuning

From Table 4.11 and Figure 4.18, it is found that, after PSS design/tuning, the number of target modes, which have a damping less than 5% is reduced from 262 to 15. The corresponding damping is also dramatically improved, as illustrated by Figure 4.19.

All the modes related to the target generators are also significantly improved, which is shown in Figure 4.20. At the same time, note Table 4.11, the number of total modes of all specified generators decreased from 433 to 340 after PSS design/tuning, as some of the modes related to the specified generators disappear from the new system model with the designed/tuned PSS.

However, Table 4.11 and Figure 4.19 show there are still 15 poorly damped modes that cannot satisfy the performance requirement after PSS design/tuning. The reason is explained as follows:

The study shows that the physical nature of all the unsatisfied modes is inter-area oscillation modes, in which the target generator has a high participation factor. Although these modes are not the objective for this task of PSS design/tuning, their appearance is due to the fact that the local mode computation option in SSAT sometimes converges to inter-area modes if the considered generator is the dominant participant in these modes. Since the inter-area modes relate to a large amount of machines, and an individual unit contributes very little to the overall damping of an inter-area mode, the incremental damping due to the designed/tuned PSS on one unit is generally very small. Therefore, the inter-area modes cannot satisfy the performance requirement only with the consideration of specified generator.

4.2.4.2 PSS Design/Tuning for Specified Modes

In this task, PSS is designed /tuned to make all poorly damped inter-area modes between 0.1 Hz to 1.0 Hz satisfy the performance requirement, which is specified as a minimum damping of 3%. The main steps include:

Step 1: Get eigenvalue information about the original oscillation modes between 0.1 Hz and 1.0 Hz, which is shown in Table 4.8. Identify the target modes with a

damping less than 3%, and deduce the mode nature from the eigenvector results in SSAT. All the results are listed in Table 4.12.

Table 4.12 Original modes with damping less than 3% before PSS design/tuning

Mode No.	Frequency (Hz)	Damping (%)	Mode nature
1	0.1699	-7.44	Local
2	0.8773	0.81	Local
3	0.8613	1.09	Local
4	0.5809	1.26	Inter-area
5	0.6279	1.27	Inter-area
6	0.6504	1.32	Local
7	0.9621	1.42	Local
8	0.914	1.44	Local
9	0.9615	1.87	Inter-area
10	0.4535	2.28	Inter-area
11	0.8808	2.43	Inter-area
12	0.9118	2.68	Inter-area
13	0.7747	2.69	Inter-area
14	0.8563	2.86	Inter-area
15	0.976	2.96	Inter-area

In Table 4.12, in total there are 15 modes with damping less than 3%, 6 local modes and 9 inter-area modes.

Step 2: Analyze the target modes -- inter-area modes with a damping less than 3% between 0.1 Hz and 1.0 Hz.

Table 4.13 is derived from Table 4.12 by taking out of all the local modes, then all the modes remaining are the target modes to be considered for PSS design/tuning.

Table 4.13 Target modes to be considered

Mode No.	Frequency (Hz)	Damping (%)	Mode nature
1	0.5809	1.26	Inter-area
2	0.6279	1.27	Inter-area
3	0.9615	1.87	Inter-area
4	0.4535	2.28	Inter-area
5	0.8808	2.43	Inter-area
6	0.9118	2.68	Inter-area
7	0.7747	2.69	Inter-area
8	0.8563	2.86	Inter-area
9	0.976	2.96	Inter-area

After that, the candidate generator list is obtained by analyzing the participation factor table from SSAT of each target mode. Table 4.14 lists the corresponding information. Only the generators with a participation factor above 0.2 are to be considered as the candidate for PSS design/tuning. Totally there are 68 candidate generators are determined. According to the statistic information in Table 4.15, except for 12 generators, which are not suitable for PSS design/tuning because no exciter is available, 52 of them need to be equipped with new PSS, and retuning should be done for the other 4 generators with existing PSS. Therefore, there are 56 target generators to be considered for the PSS design/tuning.

Table 4.14 Information of participation factor for the target modes

Mode No.	Frequency (Hz)	Damping (%)	Candidate Generators
1	0.5809	1.26	4
2	0.6279	1.27	4
3	0.9615	1.87	3
4	0.4535	2.28	2
5	0.8808	2.43	15
6	0.9118	2.68	13
7	0.7747	2.69	16
8	0.8563	2.86	16
9	0.976	2.96	15
Total			68

Table 4.15 Information of the candidate machines

No Exciter	Add new PSS	Tune PSS	Total
12	52	4	68

Similar to PSS design/tuning for specific generators, the generators with excitation system unsuitable for PSS design/tuning are dropped from the candidate generator list based on the simple criteria described in Section 3.8.3. Thus, there are 34 generators left for PSS design/tuning, which are shown in Table 4.16.

Table 4.16 Information of PSS to be designed/tuned

PSS	Dropped	Left	Total
New PSS	21	31	52
Existing PSS	1	3	4
Total	22	34	56

Step 3: Analyze PSS design/tuning results.

According to Table 4.16, 31 new PSS are designed and 3 existing PSS are tuned. With all the designed/tuned PSS, an eigenvalue scan between 0.1 Hz and 1.0 Hz is computed by SSAT. Then, all the new inter-area modes with damping less than 3% are listed in Table 4.17.

Table 4.17 New inter-area modes with damping less than 3% after PSS design/tuning

Mode No.	Frequency (Hz)	Damping (%)	Mode nature
1	0.581	1.25	Inter-area
2	0.6279	1.29	Inter-area

Compared with the target inter-area modes listed in Table 4.13, it is easy to find that the number of the poorly damped inter-area modes is reduced from 9 to 2 after PSS design/tuning in the frequency range of interest.

To check the effect of the designed/tuned PSS on all the modes within the frequency range considered, an eigenvalue analysis from 0.1 Hz to 1.0 Hz is computed by SSAT. Further comparison is carried out within different damping ranges. The results are shown in Table 4.18 and Figure 4.21. Figure 4.22 and Figure 4.23 also show the results of the damping comparison.

Table 4.18 Comparison of mode number with and without PSS design/tuning

Damping range	Range1	Range2	Rang 3	Range 4	Range 5	Total
Damping (%)	<0	0 to 1%	1% to 2%	2% to 3%	>%3	<100%
Original	1	1	7	6	60	75
New	1	1	6	0	59	67

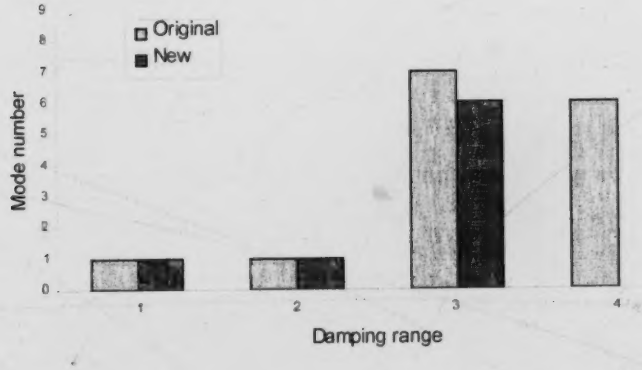


Figure 4.21 Comparison of the target modes number with and without PSS design/tuning

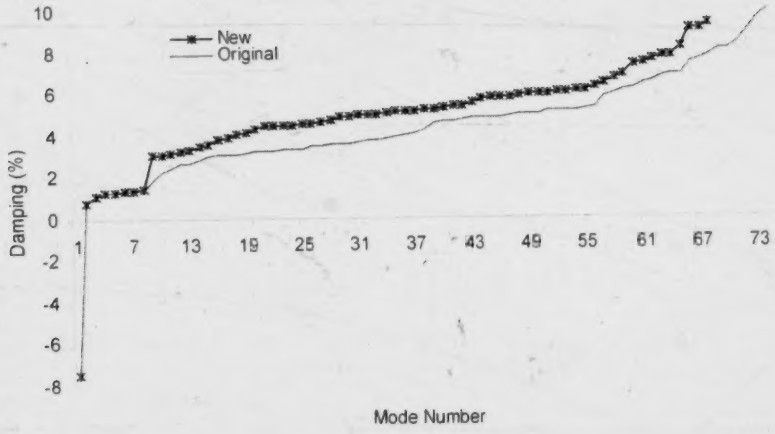


Figure 4.22 Comparison of the damping of all modes between 0.1 Hz and 1.0 Hz with and without PSS design/tuning

As it can be seen from the above plots and table, the target inter-area modes are significantly mitigated with PSS design/tuning. From Table 4.18 and Figure 4.21, it can be found that most of the target modes have a damping between 2% to 3% before PSS design/tuning, but they are eliminated from this damping range after PSS design/tuning. Figure 4.22 shows that damping of all the modes from 0.1 Hz to 1.0 Hz are also improved after the PSS are designed/tuned.

From Table 4.18, it is evident that there are still 8 modes remaining with a damping less than 3% after PSS design/tuning. Two of them are inter-area modes, which are shown in Table 4.17. The damping of these two modes is not improved because their dominant units are not considered in view of the unsuitable excitation system for PSS design/tuning. The study shows that the physical nature of all the other 6 modes is local oscillation, which can be found in Table 4.12. For these 6 local modes, mode No.1 is not considered because its dominant unit has an exciter unsuitable to install new PSS. Mode No.6 satisfies the performance requirement after adding a new PSS into its dominant generator. All the other 4 local modes cannot be improved because their corresponding dominant units are represented by classical model, which cannot be equipped with PSS.

Step 4: Mode trace of the target modes.

In this step, to compare the eigenvalue location with and without PSS design/tuning, the target inter-area modes are traced for the parameter determination procedure of PSS.

Table 4.19 Eigenvalue comparison of the target modes with and without PSS design/tuning

	Original modes		New modes	
Mode No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	0.5809	1.26	0.5810	1.24
2	0.6279	1.27	0.6279	1.28
3	0.9615	1.87	0.9671	3.92
4	0.4535	2.28	0.4460	3.35
5	0.8808	2.43	Not found	
6	0.9118	2.68	0.9214	5.39
7	0.7747	2.69	0.7818	4.85
8	0.8563	2.86	0.8658	4.59
9	0.9760	2.96	0.9789	3.99

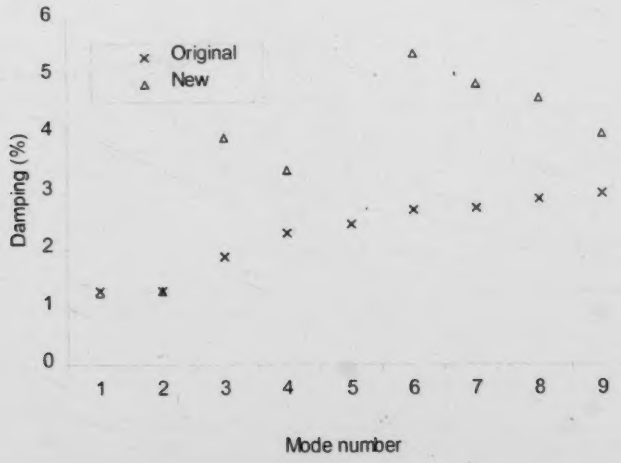


Figure 4.23 Damping comparison of the target modes with and without PSS design/tuning

As shown in Table 4.19 and Figure 4.23, the damping of the nine target inter-area modes is compared with that of new modes after PSS design/tuning. In Table 4.19, except for mode No.1 and mode No.2, which are not improved due to the reason described in step 3, all the other 7 target modes are effectively improved to satisfy the damping requirement after PSS design/tuning. In particular, mode No.5 disappears from the frequency range concerned after PSS design/tuning.

The following plots from Figure 4.24 to Figure 4.32 show the mode trace for each target mode with the setting of all PSS parameters, which include the considered time constants and gains. In each plot, the starting point refers to the eigenvalue location of the original target mode and the end point is that of the new mode with the designed/tuned PSS.

In Figure 4.24, it seems that mode No.1 deteriorate after the PSS design/tuning. However, eigenvalue results in Table 4.19 show that, for both mode No.1 and mode No.2, the damping difference between the original PSS and new PSS is so small that it can be ignored. Figure 4.28 shows that mode No.5 disappears from the frequency range considered during the trace process. The damping improvement of all the other modes is apparent.

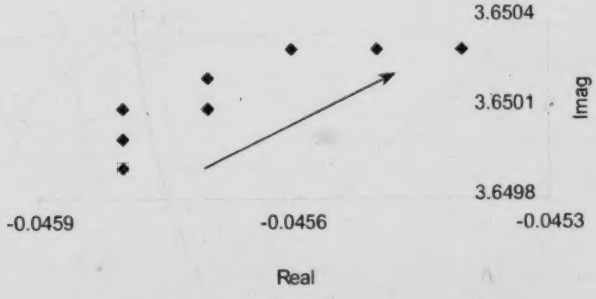


Figure 4.24 Mode trace of target mode No.1

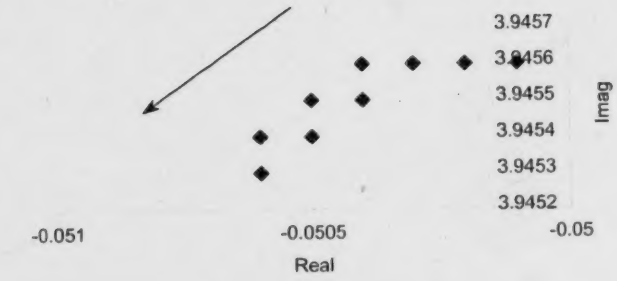


Figure 4.25 Mode trace of target mode No.2

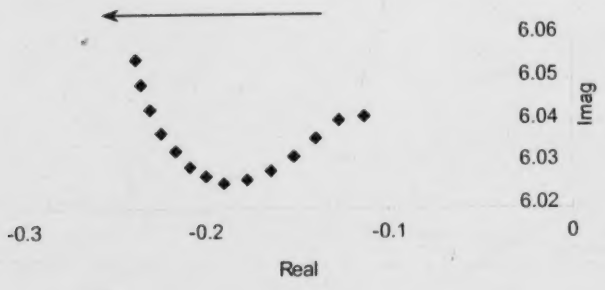


Figure 4.26 Mode trace of target mode No.3

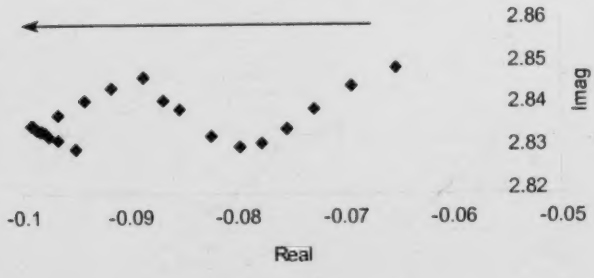


Figure 4.27 Mode trace of target mode No.4

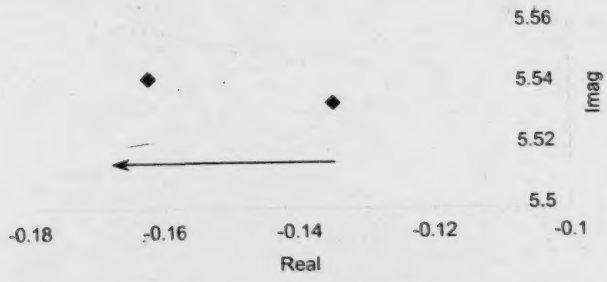


Figure 4.28 Mode trace of target mode No.5

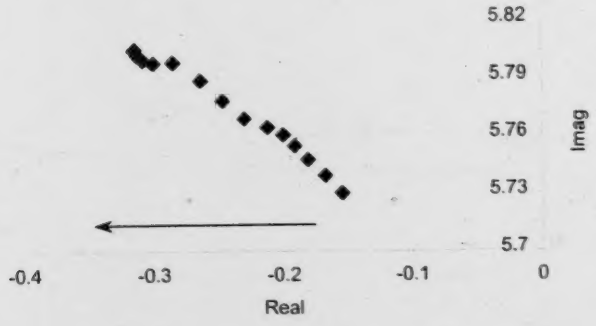


Figure 4.29 Mode trace of target mode No.6

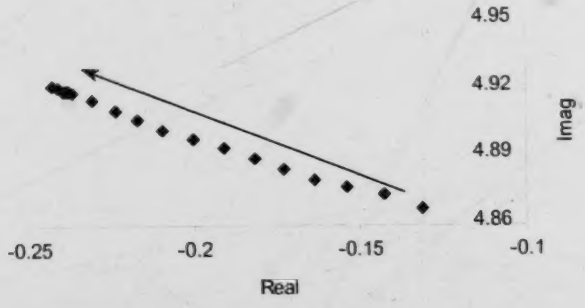


Figure 4.30 Mode trace of target mode No.7

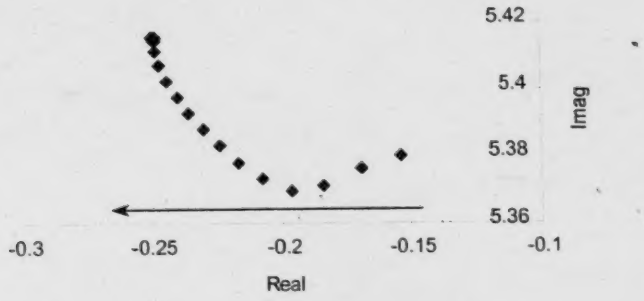


Figure 4.31 Mode trace of target mode No.8

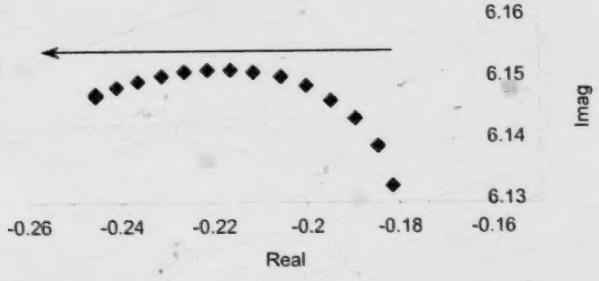


Figure 4.32 Mode trace of target mode No.9

4.2.5 Discussion

In this section, interaction and impact between PSS design/tuning results of the above two tasks are discussed.

4.2.5.1 Impact of PSS on All Modes

In Section 4.2.4.1, PSS are designed/tuned for the poorly damped local modes of the specified generators. To check its effect on the overall oscillation modes, an eigenvalue scan between 0.1 Hz and 3.0 Hz is calculated by SSAT with these designed/tuned PSS, and the new modes found are compared with the original ones before PSS design/tuning.

Our interest is the effect of PSS design/tuning on the inter-area modes with a low frequency between 0.1 Hz to 1.0 Hz; the corresponding information is listed in Table 4.20 and Table 4.21. It can be seen that, with all the designed/tuned PSS for local modes, the mode number from 0.1 Hz to 1.0 Hz is reduced from 74 to 57. Especially, the poorly damped inter-area modes with a damping less than 5% are significantly mitigated and the number decreases from 38 to 11. The number of poorly damped local modes is also reduced from 12 to 9. For the local modes that do not satisfy the performance requirement after PSS design/tuning, it is found that the corresponding dominant unit is either not in service or has an excitation system unsuitable for PSS design/tuning.

Table 4.20 Comparison of the mode number with and without PSS design/tuning

Mode	Original number	New number
Inter-area (Damping<5%)	38	11
Local (Damping<5%)	12	9
Total (Damping<5%)	50	20
All modes (Damping<100%)	74	57

Table 4.21 Comparison of modes with damping less than 5% with and without PSS design/tuning

Original modes				New modes			
Mode No.	Frequency (Hz)	Damping (%)	Mode nature	Mode No.	Frequency (Hz)	Damping (%)	Mode nature
1	0.1699	-7.43	Local	1	0.1699	-7.44	Local
2	0.8772	0.81	Local	2	0.8774	0.81	Local
3	0.8645	1.09	Local	3	0.8613	1.09	Local
4	0.5809	1.26	Inter-area	4	0.9614	1.13	Local
5	0.628	1.27	Inter-area	5	0.914	1.44	Local
6	0.6503	1.32	Local	6	0.5803	1.48	Inter-area
7	0.9621	1.42	Local	7	0.6265	1.53	Inter-area
8	0.914	1.44	Local	8	0.9019	3.12	Local
9	0.9615	1.87	Inter-area	9	0.8788	3.12	Local
10	0.4535	2.28	Inter-area	10	0.8736	3.31	Local
11	0.8808	2.43	Inter-area	11	0.7845	3.36	Local

Table 4.21 Comparison of modes with damping less than 5% with and without PSS design/tuning (continued)

Original modes				New modes			
Mode No.	Frequency (Hz)	Damping (%)	Mode nature	Mode No.	Frequency (Hz)	Damping (%)	Mode nature
12	0.912	2.69	Inter-area	12	0.918	4.07	Inter-area
13	0.7747	2.69	Inter-area	13	0.8771	4.16	Inter-area
14	0.8563	2.86	Inter-area	14	0.9716	4.26	Inter-area
15	0.9761	2.96	Inter-area	15	0.4458	4.35	Inter-area
16	0.5108	3.05	Inter-area	16	0.8687	4.45	Inter-area
17	0.9017	3.11	Local	17	0.9811	4.52	Inter-area
18	0.8789	3.11	Inter-area	18	0.8834	4.53	Inter-area
19	0.765	3.18	Inter-area	19	0.9248	4.6	Inter-area
20	0.8762	3.2	Inter-area	20	0.8855	4.7	Inter-area
21	0.6768	3.24	Inter-area				
22	0.7294	3.27	Inter-area				
23	0.8736	3.31	Local				
24	0.7843	3.34	Local				
25	0.8242	3.35	Inter-area				
26	0.8079	3.48	Local				
27	0.5872	3.49	Inter-area				
28	0.9132	3.54	Inter-area				
29	0.4055	3.58	Inter-area				
30	0.7514	3.59	Inter-area				
31	0.9972	3.66	Inter-area				
32	0.876	3.72	Inter-area				
33	0.9735	3.73	Inter-area				
34	0.8393	3.78	Inter-area				
35	0.9674	3.86	Inter-area				
36	0.8575	3.95	Inter-area				
37	0.8651	4.02	Inter-area				
38	0.7215	4.22	Inter-area				
39	0.6044	4.53	Inter-area				
40	0.9728	4.61	Inter-area				
41	0.7909	4.62	Inter-area				
42	0.9882	4.71	Inter-area				

Table 4.21 Comparison of modes with damping less than 5% with and without PSS design/tuning (continued)

Original modes				New modes			
Mode No.	Frequency (Hz)	Damping (%)	Mode nature	Mode No.	Frequency (Hz)	Damping (%)	Mode nature
43	0.8472	4.77	Inter-area				
44	0.3196	4.77	Inter-area				
45	0.6929	4.78	Inter-area				
46	0.9251	4.8	Local				
47	0.8063	4.89	Inter-area				
48	0.9355	4.92	Local				
49	0.8512	4.97	Inter-area				
50	0.97	4.97	Inter-area				

All the other modes with frequency between 1.0 Hz to 3.0 Hz are also analyzed. Since these modes are all local ones, the effect of the designed/tuned PSS has been described in Section 4.2.4.1.

Therefore, the designed/tuned PSS are shown to be capable of not only damping the local oscillatory mode, but also can provide some suppression of the inter-area oscillations.

4.2.5.2 Impact of PSS on Local Modes

In Section 4.2.4.2, PSS are designed /tuned for 34 generators to improve the poorly damped inter-area modes. To check the impact on the local modes, this section will calculate and analyze all the local modes of these 34 target generators with the designed/tuned PSS. The local modes of the generators can be classified into the following three cases:

- Case 1: Original local modes without PSS design/tuning.

- Case 2: New local modes where all the designed/tuned PSS are installed simultaneously.
- Case 3: New local modes where the designed/tuned PSS are installed one by one.

Figure 4.33, Figure 4.34 and Table 4.22 show the comparison between the results of Case 1 and Case 2.

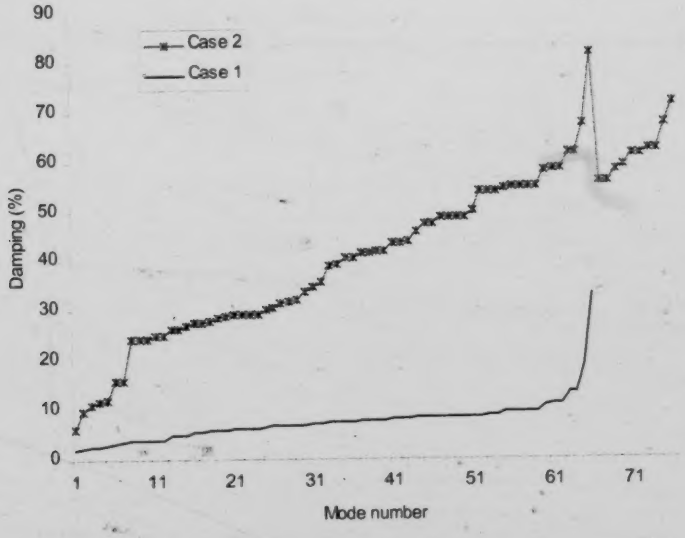


Figure 4.33 Comparison of damping for local modes between Case 1 and Case 2

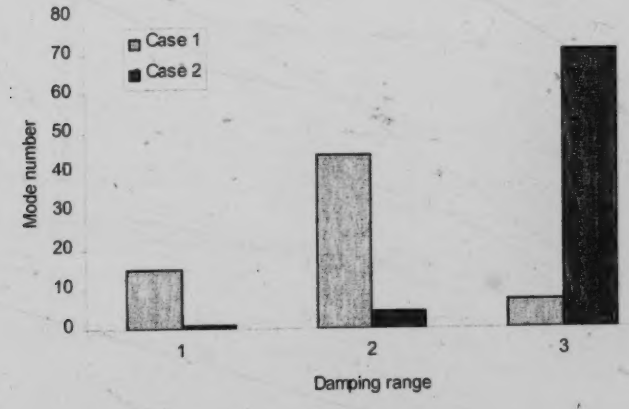


Figure 4.34 Comparison of local modes number between Case 1 and Case 2

Table 4.22 Comparison of local modes number between Case 1 and Case 2

Damping range	Range1	Range2	Rang 3	Total
Damping (%)	0 to 5%	5% to 10%	>10%	<100%
Case 1	15	44	7	66
Case 2	1	4	71	76

In Table 4.22, for all the target generators, most of their original local modes have a damping less than 10%. However, after the installation of all PSS designed/tuned for the inter-area mode, more than 90% of the poorly damped local modes are significantly improved with damping exceeding 10%. Therefore, besides inter-area modes being improved by the designed/tuned PSS, damping of the local modes of the corresponding target generators is also effectively enhanced.

Figure 4.35, Figure 4.36 and Table 4.23 show the comparison of the Case 1 and Case 3 results. A similar conclusion to that of the above comparison can be obtained. In Figure 4.35 and Figure 4.36, after PSS are designed/tuned for the target inter-area mode, the damping of the local modes as well as of the inter-area modes is effectively improved.

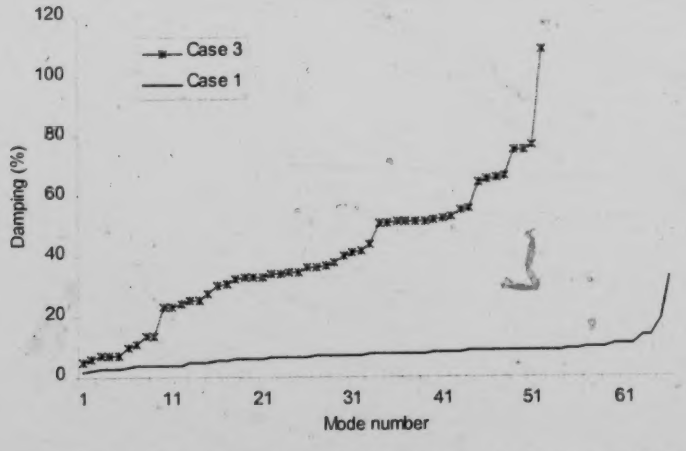


Figure 4.35 Comparison of the damping of all local modes between Case 1 and Case 3

Table 4.23 Comparison of local modes number between Case 1 and Case 3

Damping range	Range1	Range2	Rang 3	Total
Damping (%)	0 to 5%	5% to 10%	>10%	<100%
Case 1	15	44	7	66
Case 3	5	9	38	52

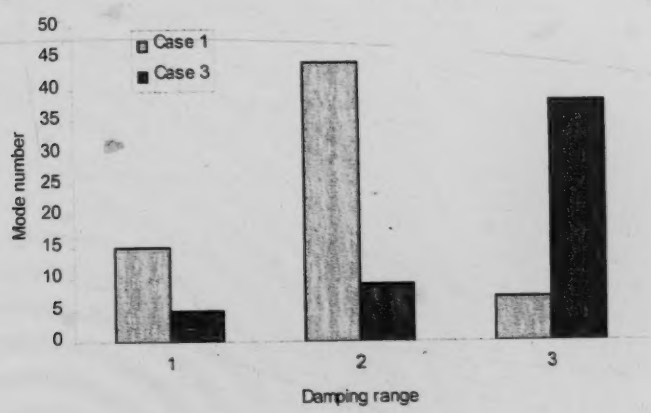


Figure 4.36 Comparison of the local modes within different damping range between Case 1 and Case 3

Figure 4.37 and Figu4.38 and Table 4.24 show the comparison results of all three cases.

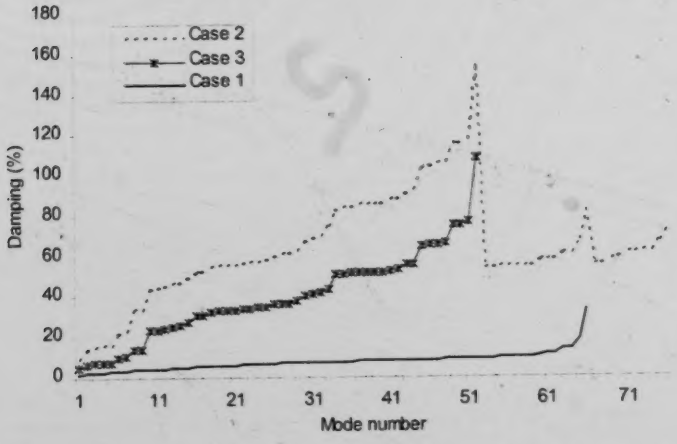


Figure 4.37 Comparison of the damping for all local modes for three cases

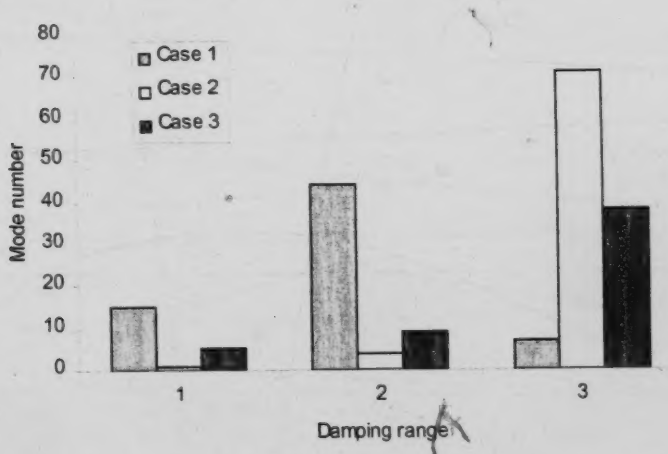


Figure 4.38 Comparison of the local modes number within different damping range

Table 4.24 Comparison of local modes number for three cases

Damping range	Range1	Range2	Rang 3	Total
Damping (%)	0 to 5%	5% to 10%	>10%	<100%
Case 1	15	44	7	66
Case 2	1	4	71	76
Case 3	5	9	38	52

As evident from Figure 4.37, Figure 4.38 and Table 4.24, both for Case 2 or Case 3, the damping of local modes with the designed/tuned PSS is effectively improved compared with that of the original system. Since the results in Case 2 are better than that of Case 3, it is reasonable to say that the interaction between the designed/tuned PSS is helpful to improve the poorly damped local modes when the designed new PSS are installed simultaneously.

4.2.6 Comments

From the comparison of the PSS design/tuning results for above two objectives, it is found that the favorable influences between them exist. Either of the objectives will be

benefit from the PSS design/tuning for the other objective. Also, it is more difficult to achieve the levels of damping of inter-area modes comparable to those for local-area modes, because PSS design/tuning for inter-area modes tend to suffer from the following drawbacks even when PSS are properly tuned:

- The contribution to damping by individual PSS units may be small due to lower participation factors;
- Interactions between PSS of different units may be deleterious to damping;
- Only a few groups of generators fitted with PSS units may contribute significantly to the damping of the mode.

The chosen performance criteria of damping for inter-area mode, which is less than damping of local modes, also reflects this point.

4.3 Conclusion

This chapter has demonstrated the performance of the proposed PSS design/tuning toolbox by studying two cases.

Case 1 focuses on the behavior of the stabilizer itself; results with different objective stabilizer and different target parameters to be set are compared. The analysis shows that for the same PSS design/tuning objective, not only the existing PSS can be retuned, but also new PSS can be added to improve the system performance. For the same PSS, different parameter setting objectives can be specified. All the results of this case demonstrate that this proposed toolbox is flexible and practical for PSS design/tuning.

Case 2 focuses on the system behavior; results of different PSS design/tuning objective are analyzed. Two forms of eigenvalue performance are studied, one concerns the local modes of the specific generators; the other concerns the inter-area modes within the specified frequency range. Correspondingly, two tasks of PSS design/tuning are employed in order to improve the power system's performance. After designing some new PSS and tuning the existing PSS, the behavior of power system is improved to satisfy the performance requirement. All the results of this case prove that the proposed PSS design/tuning toolbox is simple to use and suitable for large-scale system. At the same time, it also shows that PSS design/tuning is a very attractive and effective solution to the electromechanical oscillation-damping problem.

Chapter 5

Conclusion

This chapter puts forward some general conclusions on the results of this thesis and suggests some possible future research work.

5.1 Conclusion

This thesis is entirely devoted to the development of a toolbox that automates the PSS design/tuning procedure for power systems. This goal is achieved through a series of steps.

In the orientation of Chapter 1, the concept of power system stability and characteristics of power system oscillation was presented. As a main problem of small-signal stability, insufficient damping of oscillations may disrupt the normal, smooth operation of the system and may lead to a serious operating problem. These oscillations must be considered in planning, designing and operating a large power system. The necessity and purpose of design/tuning PSS, which is one of the supplementary controls of power system oscillation, was present.

The second step was to present the methods for power system oscillation analysis and PSS design/tuning. Modal analysis is well suited for power system oscillation analysis. Modes of generator rotor oscillations, which tend to be mixed with each other, can be separated and identified by eigenvalue analysis. The eigenvalue associated with each mode gives a clear and precise indication of oscillation frequency and damping. The effects of generators on each eigenvalue are revealed by participation factors. Thus valuable information is provided to enhance damping of a system and to determine the location of PSS. As the most cost effective supplementary control device, PSS adds

damping to the generator rotor oscillations by adjusting generator excitation with auxiliary stabilizing signal. The theoretical aspects of PSS including types, characteristics and design/tuning objectives were introduced in Section 2.2. After PSS parameters were determined, both small signal and large signal stability test should be carried out to evaluate the effect of the designed/tuned stabilizer on the overall system performance. Based on industry experience, some appropriate performance criteria were recommended for PSS design and performance verification. The final section in Chapter 2 presented and compared several PSS design/tuning techniques. Power system characteristics pose a number of difficulties in the application of some techniques due to the liberalization of the power system equations, which may lead to high-order state matrices that are non-sparse, as well as restriction of the large number of system states. It was proved that frequency response based phase compensation combined with gain margin technique is the most suitable approach for this project.

The third step introduced the implementation of a toolbox of the proposed PSS design/tuning approach. A PSS parameter determination method was described, an optimal design of time constants was developed to provide the desired phase compensation and gain tuning was based on gain margin and mode trace to supply the desired damping for the considered objective. The detail logic of the proposed PSS design/tuning toolbox was given in Section 3.6. The developed toolbox allows the program written for using SSAT and TSAT. SSAT is used to identify the nature of power system oscillation while TSAT simulates the system dynamic behavior in time-domain. Some factors affecting the performance of the designed/tuned PSS were analyzed through simulation. It was shown that PSS type, PSS structure and excitation system type had important influence on the effective damping contribution of PSS. Due to the consideration of the project scope, the issue of robustness problem was not considered.

Finally, the results of case studies using the proposed PSS design/tuning toolbox were presented in Chapter 4. This toolbox was demonstrated to be feasible and easy to be implemented by Case1 study with different PSS design/tuning objectives and

specifications. The study of Case 2 indicated that the proposed toolbox was capable of providing straightforward and practical PSS design/tuning analysis for large-scale power systems. It was also shown that PSS design/tuning is an attractive and effective way to control power system oscillation.

The main contributions of this thesis can be summarized as follows:

1. A computer software package for PSS design/tuning was developed, which integrates the existing design/tuning methods and specialized analysis tools into a toolbox. Compared with other tools for PSS design/tuning, this approach is intuitive and it makes PSS design/tuning task straightforward by providing an optimally designed or tuned PSS.

2. The PSS design/tuning approach in this thesis is simple to be implemented, which makes it practical enough for industry application, especially for large-scale power systems.

3. Based on the proposed method, the concerning PSS design/tuning objectives, constraints and requirements of the considered parameters can be flexibly specified. An overall optimal design/tuning result can be achieved.

4. Extensive case studies were conducted to verify the derived toolbox and the performance of the designed/tuned PSS. All results of comparison with situation before PSS design/tuning show that the power system with the designed/tuned PSS can achieve a better performance than a system without PSS design/tuning.

5.2 Future Work

Although this thesis presents extensive studies on PSS design/tuning implementation, there are still a number of areas where further research is advisable. It is suggested that future studies include the follow aspects.

5.2.1 Robust Control Design with Various Conditions

The ability of a controller to behave in a desired way while system parameters vary is referred to as robustness of the controller.

In this thesis, PSS is only designed to perform specified tasks assuming invariant operating conditions. Although PSS can be designed to behave appropriately in a wide range of system conditions, they cannot cope with all system conditions that can rise. Since it is very hard to foresee all possible conditions, particularly during contingency, it is important to investigate the robustness of PSS with various conditions, which they were not designed for.

5.2.2 Coordinated PSS Design/Tuning

Coordinated design means the simultaneous tuning of power system controllers to realize the full potential of the control scheme.

Until recent years the coordination of PSS as a design requirement has not been emphasized by the industry, mainly because various approaches based on a single-machine-infinite-bus model, and coupled with classical control system design tools have sufficed in many cases. As decentralized controllers with local measurements and closed-loop operation, PSS provide high quality and reliable control. However, if PSS are not properly designed or tuned, the performance of power systems may be severely degraded. In particular, unexpected adverse interactions between PSS and between PSS and other power system components are potential hazards to power systems. A number of control

interactions that have actually occurred in real power systems, or have been identified in system studies and analysis [7], [10], [27].

In this project, interactions between PSS and other relevant power system components, e.g. AVR, are ignored, but they can affect the performance of PSS.

The approach of coordinated design should minimize or prevent deleterious interactions among controllers, ensure the dynamic and steady state performance criteria for the system are satisfied, and provide a simple procedure for tuning the controllers. Many coordination controller design methods are based on optimization methods and the artificial intelligence techniques, such as multivariable, adaptive, fuzzy, neural and expert systems have been employed to provide an automated procedure for the simultaneous coordination of damping controllers design in large, interconnected power systems [21], [32], [50]. These controllers, though not implemented in practice completely, can handle the issues of coordination.

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Appendices

Appendix A Model of Single Machine Infinite Bus System

According to generator swing equation (per unit), we have:

$$\frac{d\Delta\omega_r}{dt} = \frac{1}{2H}(T_m - T_e - K_D\Delta\omega_r)$$
$$\frac{d\delta}{dt} = \omega_0\Delta\omega_r \tag{1}$$

Convert it by Laplace transform:

$$s\Delta\omega_r = \frac{1}{2H}(T_m - T_e - K_D\Delta\omega_r)$$
$$s\delta = \omega_0\Delta\omega_r \tag{2}$$

where

$\Delta\omega_r$ is the per unit speed deviation,

δ is rotor angle in electrical radians,

ω_0 is the base rotor electrical speed in radians per second,

H is the rotor mechanical inertia constant.

Linearizing the above equations yields

$$s\Delta\omega_r = \frac{1}{2H}(\Delta T_m - \Delta T_e - K_D\Delta\omega_r)$$
$$s\Delta\delta = \omega_0\Delta\omega_r \tag{3}$$

With the generator represented by the classical model and all resistance neglected, the air-gap power P_e equals to terminal power P, and for the single machine infinite bus model, the relationship between air-gap torque T_e and air-gap power P_e is

$$T_e \approx P_e \tag{4}$$

with

$$P_e = P = \frac{E'E_B}{X_T}\sin\delta \tag{5}$$

So

$$T_e \approx \frac{E' E_B}{X_T} \sin\delta \tag{6}$$

Linearzing the above equation in the vicinity of an operating condition δ_0:

$$\Delta T_e = \frac{E' E_B}{X_T} \cos\delta_0 \Delta\delta \tag{7}$$

Substitute equation (7) into equation (3). Then the following equations are obtained:

$$\begin{aligned} s\Delta\omega_r &= \frac{1}{2H}(\Delta T_m - K_s\Delta\delta - K_D\Delta\omega_r) \\ s\Delta\delta &= \omega_0\Delta\omega_r \end{aligned} \tag{8}$$

with

$$K_s = \frac{E' E_B}{X_T} \cos\delta_0 \tag{9}$$

where

K_S is synchronizing torque coefficient,

K_D is damping torque coefficient.

An equation about $\Delta\delta$ is obtained from equation (8):

$$s^2\Delta\delta + \frac{K_D}{2H} s\Delta\delta + \frac{K_S}{2H}\omega_0\Delta\delta = \frac{\omega_0}{2H}\Delta T_m \tag{10}$$

Solve the corresponding characteristic equation:

$$s^2 + \frac{K_D}{2H} s + \frac{K_S}{2H}\omega_0 = 0 \tag{11}$$

Compare with the general form of characteristic equations:

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \tag{12}$$

Therefore, the frequency and damping ratio can be represented as:

$$\omega_n = \sqrt{K_S \frac{\omega_0}{2H}} \tag{13}$$

$$\zeta = \frac{1}{2}\frac{K_D}{2H\omega_n} = \frac{1}{2}\frac{K_D}{\sqrt{K_S 2H\omega_0}} \tag{14}$$

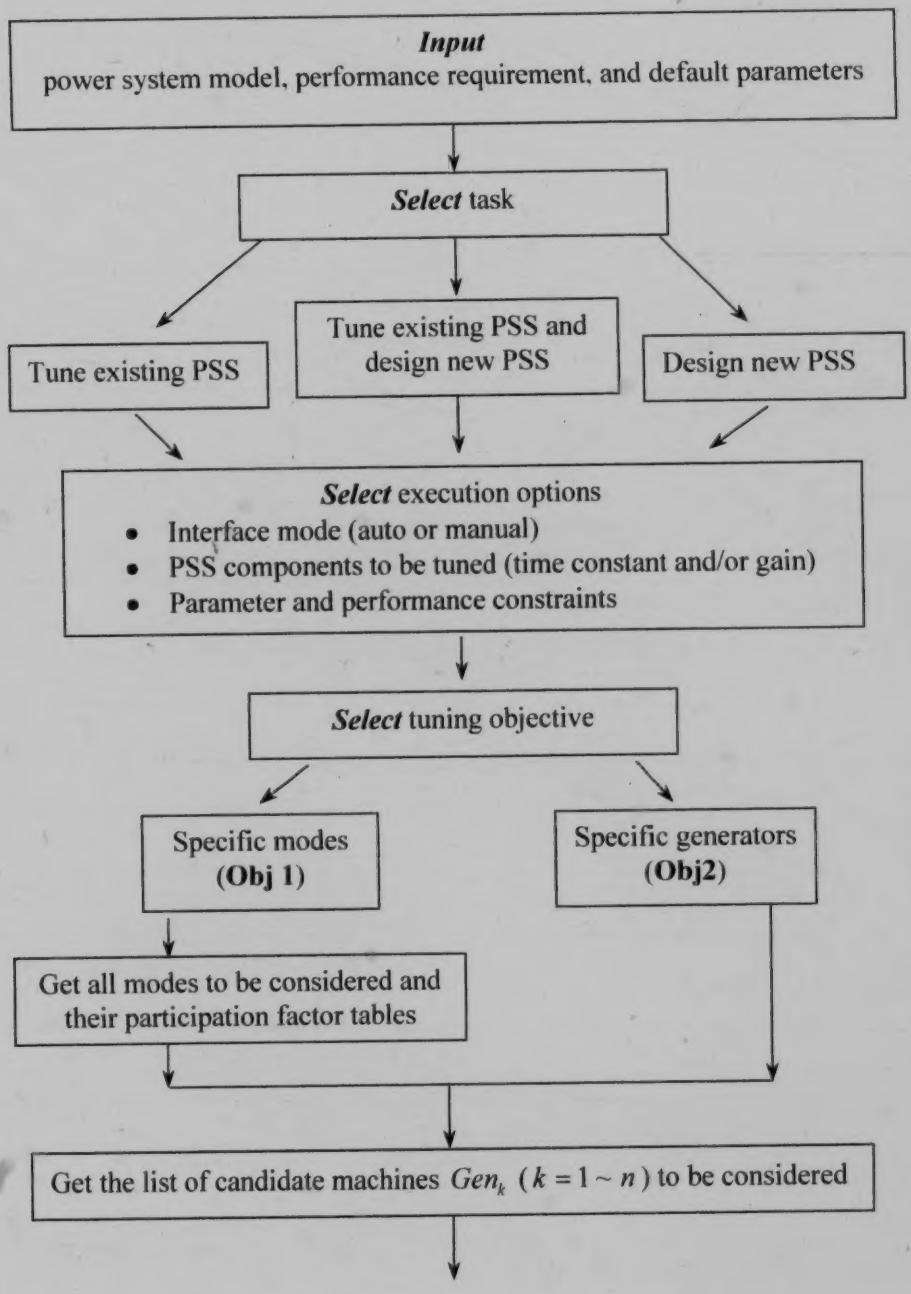
The synchronizing torque coefficient K_S and damping torque coefficient K_D is given by the following equations:

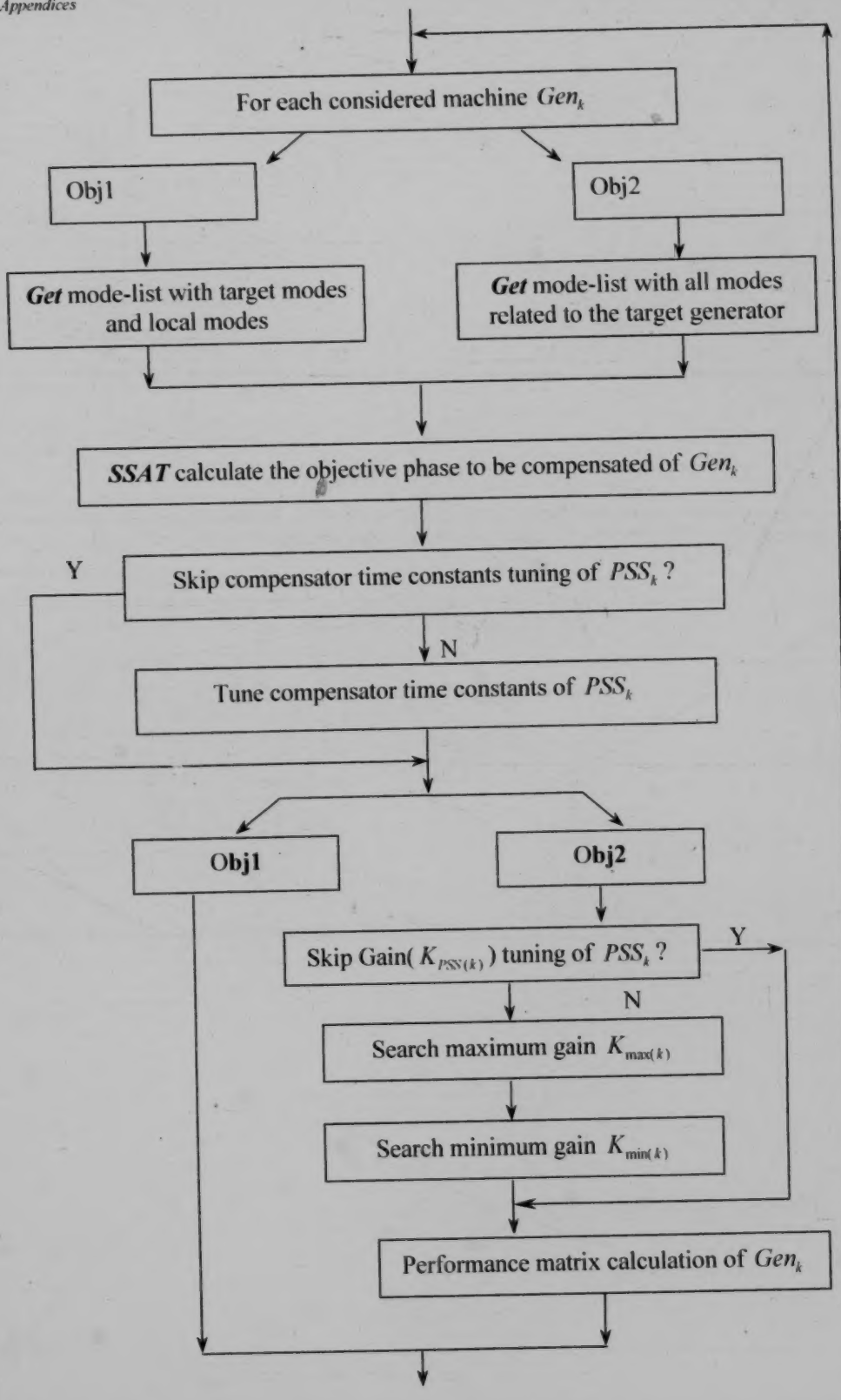
$$K_S = \omega_n^2 \frac{2H}{\omega_0} \tag{15}$$

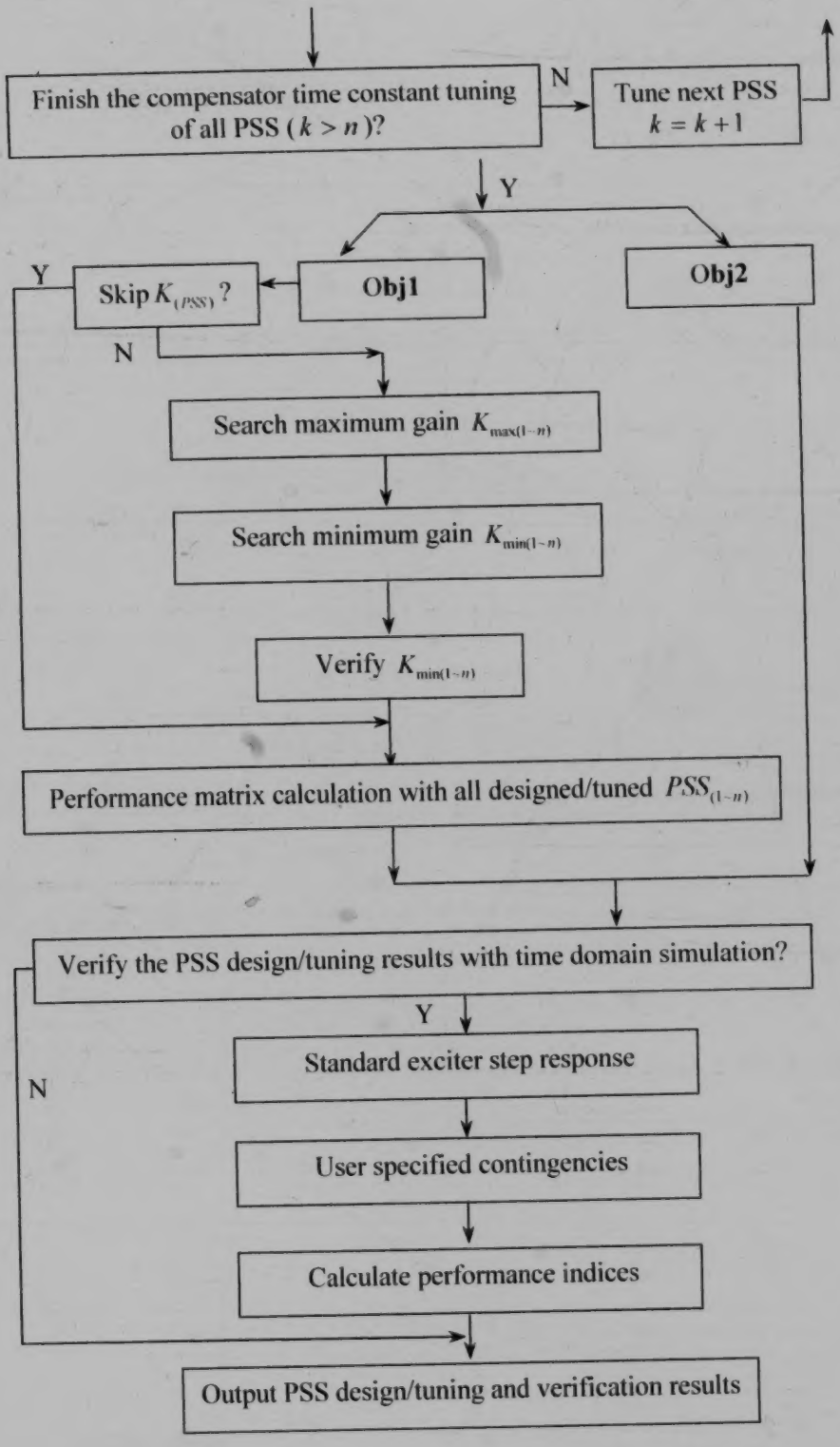
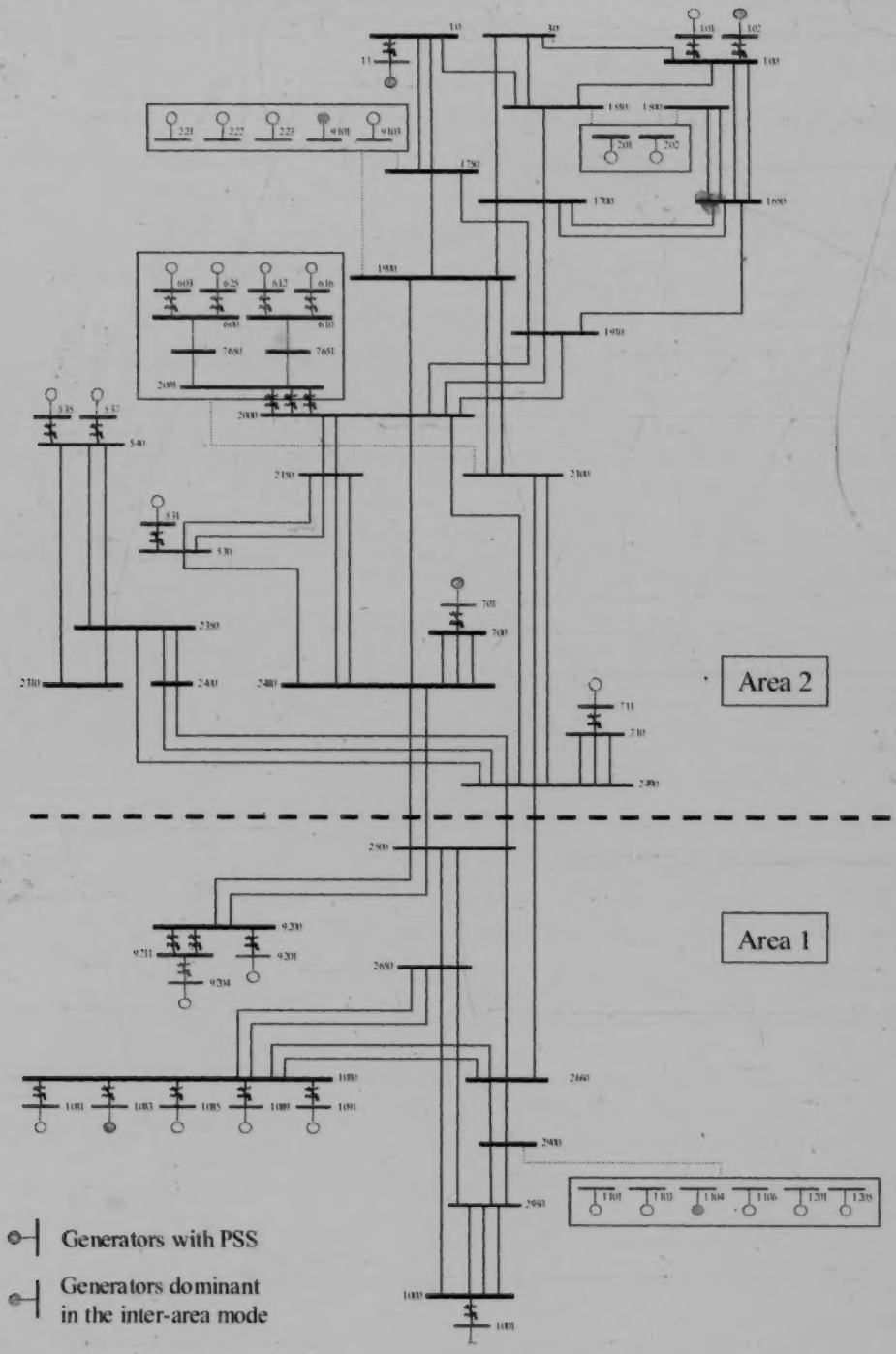
$$K_D = 4H\omega_n\zeta = 2\zeta\sqrt{K_S 2H\omega_n} \tag{16}$$

Obviously, when the frequency ω_n decreases, synchronizing torque coefficient K_S decreases and damping ζ decreases too. For the same frequency, damping ζ increases if damping torque coefficient K_D increases.

Appendix B Computation Program Flow Chart of PSS Design/Tuning


Input
power system model, performance requirement, and default parameters
Select task
Tune existing PSS
Tune existing PSS and design new PSS
Design new PSS
Select execution options
• Interface mode (auto or manual)
• PSS components to be tuned (time constant and/or gain)
• Parameter and performance constraints
Select tuning objective
Specific modes (Obj 1)
Specific generators (Obj2)
Get all modes to be considered and their participation factor tables
Get the list of candidate machines Gen_k ($k = 1 \sim n$) to be considered


For each considered machine Gen_k
Obj1
Obj2
Get mode-list with target modes and local modes
Get mode-list with all modes related to the target generator
SSAT calculate the objective phase to be compensated of Gen_k
Y
Skip compensator time constants tuning of PSS_k ?
N
Tune compensator time constants of PSS_k
Obj1
Obj2
Skip Gain($K_{PSS(k)}$) tuning of PSS_k ?
Y
N
Search maximum gain $K_{max(k)}$
Search minimum gain $K_{min(k)}$
Performance matrix calculation of Gen_k


Finish the compensator time constant tuning of all PSS ($k > n$)?
N
Tune next PSS $k = k + 1$
Y
Y
Skip $K_{(PSS)}$?
Obj1
Obj2
N
Search maximum gain $K_{max(1\sim n)}$
Search minimum gain $K_{min(1\sim n)}$
Verify $K_{min(1\sim n)}$
Performance matrix calculation with all designed/tuned $PSS_{(1\sim n)}$
Verify the PSS design/tuning results with time domain simulation?
Y
N
Standard exciter step response
User specified contingencies
Calculate performance indices
Output PSS design/tuning and verification results

Appendix C Single Line Diagram of Case1